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A DESIGN METHODOLOGY IS PRESENTED WHICH THE DESIGNER MAY USE TO IMPROVE THE RESISTANCE OF COMPOSITE STRUCTURES TO LOW-VELOCITY IMPACTS TYPICAL OF THOSE EXPERIENCED IN THE MAINTENANCE, HANDLING, SERVICE, AND MANUFACTURING OF COMPOSITES. SIMPLE ANALYSIS AND EXPERIMENTAL TECHNIQUES, WHICH MAY BE USED IN THE EARLY STAGES OF CONCEPT EVALUATION TO PROVIDE DESIGN-DECISION SUPPORT FOR IMPACT RESISTANT CONCEPTS, HAVE BEEN INVESTIGATED FOR AS4/3501-6 THERMOSET AND AS4/PEEK THERMOPLASTIC SYSTEMS. INSTRUMENTED IMPACT TESTING, STATIC LOAD-DEFLECTION TESTING, ANALYSIS (FOR HERTZIAN CONTACT BEHAVIOR) AND FINITE ELEMENT ANALYSIS (FOR PLATE BENDING RESPONSE) COMBINE TO GIVE THE DESIGNER GLOBAL-LOCAL DATA DIRECTLY USEFUL IN THE DESIGN OF COMPOSITE STRUCTURES. HOUSE OF QUALITY AND PUGH CONCEPT SELECTION TECHNIQUES ARE USED TO IDENTIFY CRITICAL CONTROL AND RESPONSE VARIABLES. THE 90°, $\varepsilon_{90°}$, STRAIN CUTOFF VALUE IS IDENTIFIED AS A CRITICAL IMPACT PERFORMANCE PARAMETER.

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DESIGNING COMPOSITE STRUCTURES FOR LOW-VELOCITY IMPACT

by

Timothy Clark Lindsay

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Materials Science

August, 1990

DESIGNING COMPOSITE STRUCTURES FOR LOW-VELOCITY IMPACT

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An old Chinese proverb, roughly translated, goes something like this, "Be careful what you ask for, you just might get it." Thus, I found myself in graduate school feeling somewhat like Tutor the Turtle beseeching Mr. Wizard for relief and respite from the rigors of graduate school. Fortunately, I found many "Mr. Wizards" willing to help me through this exciting predicament, give me guidance, encouragement, assistance but most of all friendship. It is primarily these people who I wish to acknowledge.

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One must always establish and strive for goals in life which are attainably realistic yet stretch one's own limits and capabilities. When this is done with meaningful self-awareness, concern for the process as well as the ends, and understanding of its significance to the customer then something worthwhile results, called success, professional and personal. Dr. Wilkins was my compass of experience and wisdom in this regard, and my carrot of enthusiasm for the opportunities composites offer the world. His interest in a global and practical approach to research was refreshing and renewing, and his commitment to *real* cooperation amongst academia, industry, and government toward the success of America in a competitive

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And, I am certain this is a first. thanks to Frank Robinson and the 1989-1990 Baltimore Orioles for a wonderful diversion and for showing me that one can beat the odds with hard work, dedication, and teamwork, and have fun doing it.

To my father, Sam, for instilling in me the drive to do my best (and never expecting more) and my mother, Catherine, for giving me a natural curiosity for science and love of learning, of course my thanks goes beyond words.

And saving the most important for last, I dedicate this thesis to my loving and beautiful wife, Jane, who for reasons which must be love, put up with my wailing and gnashing of teeth for these two years and expertly edited a long tedious thesis while nearly single-handedly performing the most important job in the world, raising our son

to be a thoughtful, happy, curious little boy and, I am confident, someday wise young man. To Mark, my son, thanks for providing a constant reminder to me of the things most important in life, and for the unconditional and total love of which only a child is capable. And Mark, "When I'm done typing this we'll hit a few baseballs."

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coupons subjected to low-velocity impacts. Results have been correlated with static load-deflection response of equivalent coupons in a unique test setup using the same apparatus and then correlated with a finite element analysis of the test specimens.

A 3-D static finite element analysis of a GRC, Dynatup® Model 8200 impact drop tower with standard test support fixture has been conducted to quantify the compliance of the test apparatus and demonstrate the influence of the test apparatus in the load-deflection response. The importance of a rigid standard for the installation and setup of an impact apparatus is graphically demonstrated.

Through a disciplined methodology, design of impact resistant composite structures can be improved. A set of impact design tools—beginning with a 90° strain cutoff as a lower bound of impact performance—has been developed to assist the designer in this regard. A higher order approach using experimental and analytical "cut and paste" methods has been demonstrated for supporting the design-decision phases and concept evaluation of structures based on instrumented impact test methods, static-load deflection tests, and microcomputer-based finite element analysis.

ABSTRACT

This thesis presents a methodology and set of tools which the designer can use to improve the resistance of composite structures to low-velocity impacts typical of those experienced in the maintenance, handling, service, and manufacturing of composites, typically termed tool drops. The author has investigated the role of simple analysis and experimental techniques which may be used in the early stages of concept evaluation to provide design-decision support for impact resistant concepts.

Identifying the most important customer needs and related design criteria through the application of a coherent, cohesive, and comprehensive design methodology is the first step in a successful design, and insuring that these customer needs are translated through the design, engineering, and manufacture of the product is the essence of design. The author has developed a comprehensive impact design methodology which is contextual, i.e., it is presented in the context of all other design criteria.

Instrumented impact testing has been used to identify the incipient damage load in typical unidirectional carbon fiber thermoset and thermoplastic matrix composite

CHAPTER 1
INTRODUCTION

It's what you know after you know it all that counts.

Harry S Truman

1.1 Description of the Problem and Motivation for Low-Velocity Impact Design Research

The impact response of a composite material system is significantly influenced by its structural context; therefore, impact resistance is a function of structural configuration and constraint as well as the many other factors which have been investigated over the years, such as material properties and environmental factors. Despite the fact that the global nature of the impact problem for low-velocity impact has been well documented in the literature, a comprehensive and coherent method of designing for impact has not yet been proposed.

Ideally, the designer would be able to predict damage initiation in real structures using laboratory test data and use this data in design. Simply stated, he or she would be able to predict the consequences of a local impact within the global structural context without the need for full-scale testing which is expensive, time-consuming, and ad hoc by nature. Figure 1.1 represents this notion. Unfortunately, current test and evaluation techniques do not produce design allowable metrics which can be used in designing for impact. Impact laboratory tests, such as compression-after-impact testing, have provided data of value only in screening materials and for quality control purposes.

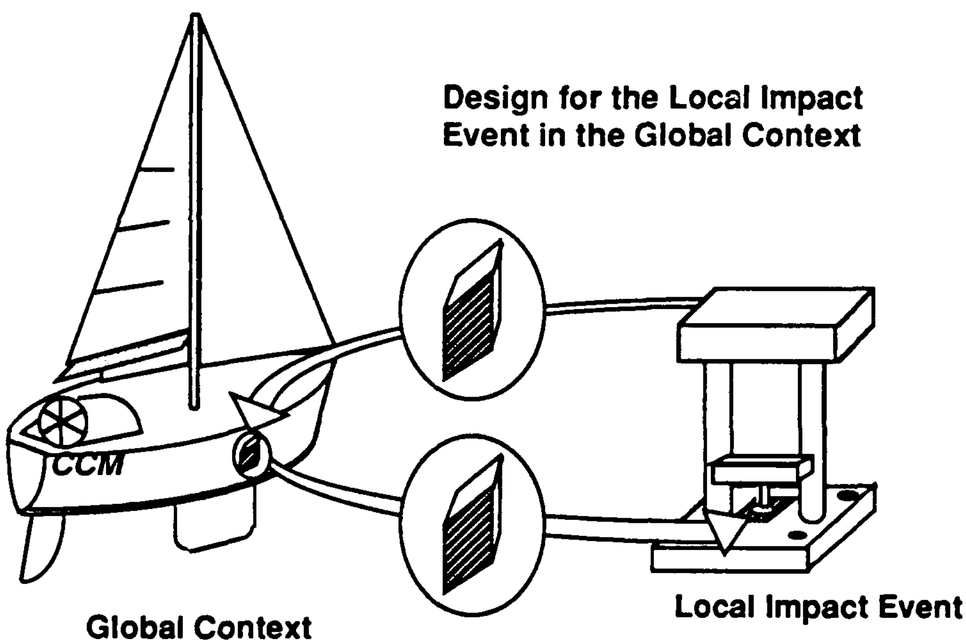

Figure 1.1 Designing for impact in the global context. This means that the structural influence (constraint and configuration) must be considered in predicting the local impact damage state.

Despite the extensive work done on the problem of impact resistance of composites, designers still need a coherent and comprehensive methodology to treat the complexity of impact, and an effective, low-cost, reliable test method to predict the effects of structural configuration and constraint on the impact properties of composites. The methods and techniques described and evaluated in this thesis suggest a novel approach for providing this capability to designers. They are founded in the philosophy of concurrent or simultaneous engineering which recognizes that all functions of design, production and support of products and systems are interrelated; therefore, they must be integrated to achieve the desired end-result of performance and customer satisfaction and all that that suggests. The framework for this design methodology has been termed *Total Quality Design* (TQD) by Henshaw and Wil[illegible] [1989] and draws elements of the *Improved Total Development Process* of Clausing [1986] and Hauser [1988].

1.2 Scope of the Research

The scope of this research was to treat low-velocity impact damage in polymer matrix composites as a *design* challenge, tying together product level design processes, impact testing and numerical analysis of test fixture apparatuses. Low-velocity impact damage is particularly troublesome because it is common (resulting from such mundane occurrences as tool drops), insidious (cannot be "seen" or is only barely visible), and deleterious (resulting in significant degradation in material and structural thermomechanical properties). From a design point of view, the research addresses a universal approach for designing for impact resistance in a structurally global context; however, test and analysis procedures focused on understanding and evaluating the effects of impact using a commercially available instrumented drop weight impact test

apparatus (GRC, Inc., Dynatup® Model 8200) and two material systems, a carbon/epoxy thermoset resin baseline (AS4/3501-6) and a carbon/polyetheretherketone (PEEK) thermoplastic resin (APC-2). Demonstrating that this laboratory test data could be used directly in design was an additional goal of the work.

In short, the research included tasks relating to design (philosophy and methodology), analysis (finite element modeling), and experimentation (test methods, strategy, and design). The interrelationships of these three areas and need to work them concurrently is critical to successful design and, the author believes, future design research. See Figure 1.2.

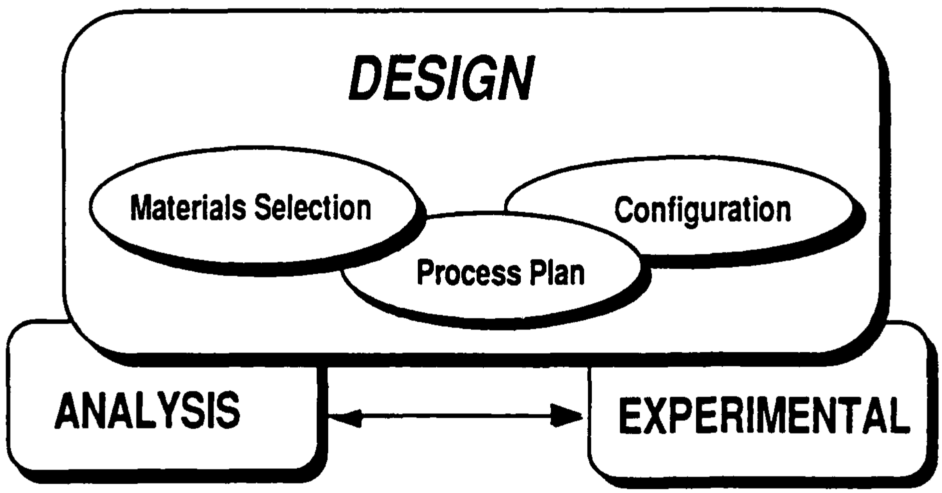

Figure 1.2 An interactive approach to design and design research. This approach must relate materials, configuration, and manufacturing issues concurrently.

1.3 Research Objectives

The premise of our work is that impact design can be approached in a more systematic, efficient, and universal manner than in the past, when a more costly, trial and error approach may have been the rule. Furthermore, that impact design, particularly where polymer matrix composites are concerned, requires a concurrent and interdisciplinary approach involving materials science, mechanical engineering, and chemical engineering disciplines executed through a TQD framework. With this in mind, the four primary objectives of this research were to:

1) Develop a coherent and comprehensive impact design methodology/framework and specific design tools for treating the impact design problem. (Chapter 3)

2) Develop and evaluate a simple and effective impact test procedure using thermoset and thermoplastic composites, and integrate this procedure with the impact design methodology (design and analysis), showing how impact test data can be used in design. (Chapters 4, 5, 6 and 7)

3) Analyze the influence of the impact test apparatus on the target structural response using microcomputer-based finite element analysis (Chapter 4) and correlate these results to impact and static test data.(Chapters 6 and 7)

4) Demonstrate and document the use of "u[illegible] friendly" microcomputer-

based design and management tools within the impact design framework. (Chapters 3 and 4)

1.4 Approach to Low-Velocity Impact Design Research

The author's approach was to integrate design, testing, theory, and analysis in order to correlate impact response in a "standard" impact test apparatus with real structures of concern to the designer. Critical impact design parameters are determined through an impact design methodology which is used to develop material and structural solutions to the impact design challenge. This methodology takes advantage of a number of design tools which use creative idea generation and disciplined evaluation [Wilkins 1989] to lead to the best solution within a design environment that recognizes the realities of tradeoffs with competing design criteria. Figure 1.3 represents the author's vision of the elements and approach to the research. Each element has a creative aspect (represented by a light bulb) and an evaluative element (represented by a computer)[1]. The focus throughout the research was on the customers and their needs.

To aid in the design effort, the methodology suggests the development and use of a dynamic Impact Design Module (IDM) which contains a database of information on impact resistant techniques and a variety of analytical and heuristic tools which can be invoked at appropriate points in the design process to assist the design-decision process. The result is a design which should provide the optimum level of impact resistance and/or damage tolerance given other design constraints. As in all real

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[1]No doubt, if the computer is a Macintosh, one would be equally justified in [illegible]ng it to represent the creative aspects of these processes—author's bias.

design problems, this TQD-based methodology recognizes that all "design for" criteria must be considered concurrently.

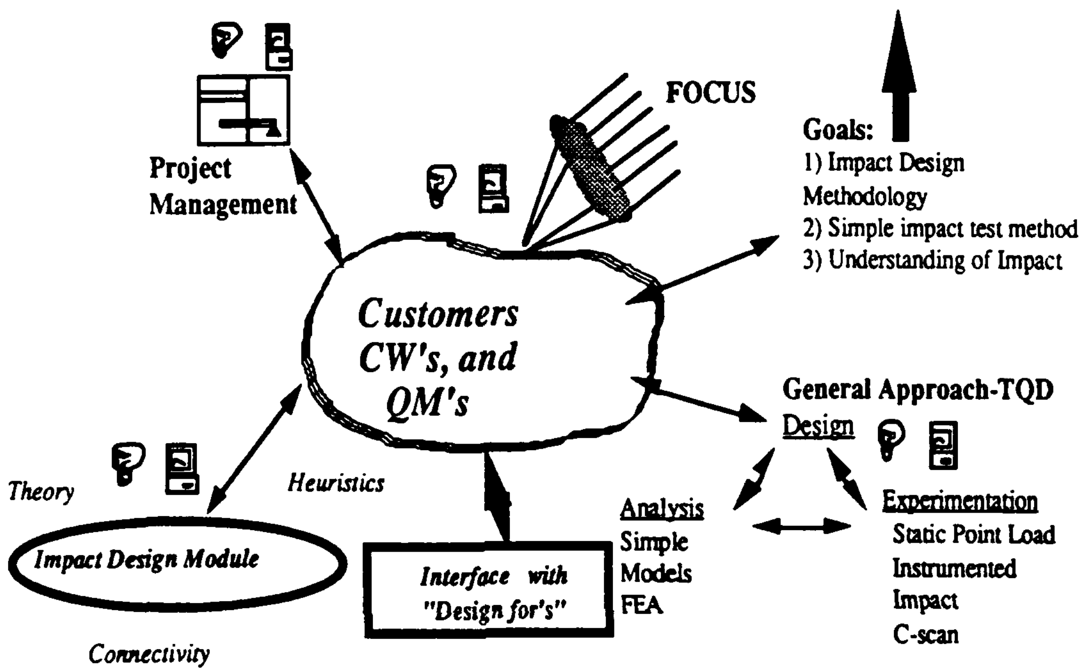

Figure 1.3 The author's "Mind Map" representing elements of low-velocity impact design approach.

A critical aspect of the research was the modeling and analysis of the impact test fixture to determine its influence (compliance) on the impact event. This modeling was done with 2-D and 3-D finite element analysis on a Macintosh™ computer platform and will be described in detail in Chapter 4. The modeled test apparatus was treated as analogous to the real structures of concern to the designer. As such, the designer could model the influence of the test fixture on the impact response (damage state) and use this

information along with test results to predict damage states in models of structural design concepts.

Experimental results (Chapter 6) were correlated with the results of the FEA and are discussed in Chapter 7. Assumptions of the use of static load-deflection data in place of more costly impact testing have been developed theoretically and supported experimentally. From these assumptions, the designer may treat impact resistance in the following stepwise fashion: 1) a lower bound of impact performance, in terms of incipient damage energy, Ei, can be determined by the transverse tensile strain of the composite, ε_{90°, 2) a higher order "cut and paste" approach using instrumented impact data and simple FEA can be used to capture the structural influence in the impact event, 3) predictive tools from the results of 1) and 2) can be develop for impact events which fit the static-dynamic assumptions and real boundary conditions.

Treating impact resistance as a design problem brings with it the responsibility of understanding a daunting range of scientific, technical, and practical issues. Chapter 2 is an attempt to capture the essence of these related issues from the literature—spanning topics from design methodologies to esoteric modeling techniques for treating 3-D nonlinear impact response in idealized composite materials. It is doubtful, despite over 370 cataloged references, that this effort was comprehensive, yet, considerable useful insight and information was derived from the task, including a list of impact design heuristics which will be useful to designers concerned with impact. Equally important was the realization of the complexities involved in the impact event and the problems this causes in predicting structural response during impact events as well as the opportunities these challenges offer for future research in this area.

CHAPTER 2

A LITERATURE SURVEY OF LOW-VELOCITY IMPACT DESIGN RESEARCH

It would be well if engineering [design] were less generally thought of, and even defined, as the art of constructing. In a certain sense it is rather the art of not constructing; or to define it rudely, but not inaptly, it is the art of doing well with one dollar, which any bungler can do with two after a fashion.

A.M. Wellington, 1887 [Tribus 1969, p. 389]

2.1 The History of the Impact Design Challenge in Composite Materials

The problems of interlaminar shear and the resulting delaminations in carbon-fiber-reinforced plastics (CFRP) from out-of-plane transient loadings, *impact*, have been well known and extensively documented in the literature since the early 1970's. Higher volume fraction carbon fiber reinforcement with much smaller diameter fibers (making uniform fiber placement in the prepreg impossible) resulted not only in superior strength and stiffness but also in a propensity for the development of matrix microcracking under a variety of loading conditions, including low-velocity impacts. Resin-poor fiber-fiber interfaces were particularly vulnerable to microcrack initiation, which resulted in subsequent int⋅.' ɹminar delamination under the shear stresses created by out-of-plane transient impact loading.

So, while in-plane properties were dramatically improved in these "advanced" carbon/epoxy composites, the damage created by low-velocity and relatively low-energy impacts was severe in terms of the residual compressive strength and stiffness, and undetectable through routine visual inspection. Despite the intervening two decades of research and development on this problem, impact damage, in particular low-velocity impact damage, in fiber-reinforced plastics remains a primary concern of material developers, design engineers, and end product users, and thus is the motivation for this thesis.

The author hopes to achieve the following objectives through this survey: 1) discuss a variety of generic and "design for impact" methodologies and philosophies and suggest how they might be used to improve the impact resistance of composite structures, 2) highlight impact failure mechanisms in composites, 3) describe the capabilities and limitations of currently accepted impact test methods, 4) spotlight a variety of techniques and methods which may improve impact resistance, 5) offer an agenda for further development of impact-resistant design tools for composites, and 6) identify some impact design heuristics for composite materials which may be included in the Impact Design Module.

The literature survey (in keeping with the objectives of the thesis) focuses on the problem of low-velocity impact, which has also been described as the "tool box syndrome"; however, much of the design philosophy discussed will be applicable to impact in general, including ballistic impacts. The remainder of the introduction is a look at where we are today and a thumbnail sketch of the key impact design issues.

2.2 Status of the Impact Design Challenge

In a recent workshop on damage tolerance of carbon-fiber-reinforced composites [Challenger 1986], among the five conclusions reached, four spoke directly to the problems of impact damage in CFRP composites: 1) damage from impact is the worst type of damage for these materials—significant reductions in the compressive strength will occur following impact; 2) very little is understood about the micromechanics of damage—hence it is impossible to predict the effect of changing the properties of the individual components (fibers, matrix, and fiber-matrix interface) on the bulk material properties; 3) better analytical models to describe the formation and growth of impact damage are badly needed; and 4) rapid NDT methods to inspect large components are required. Clearly, the effects of impact on composite materials are of concern to the composites community at large.

2.2.1 Low-Velocity Impact Testing

Standardization of impact testing has been identified as a major challenge to developing meaningful procedures for designing impact-resistant composite structures. Even in the case of standard impact tests for metals—Izod, Charpy, etc.— it is understood that the fracture toughness data obtained is valid only as an indication of relative toughness and, therefore, useful for comparing materials and for quality control purposes. The limitation of these tests for metals, and by extension these or one of the myriad non-standard tests developed for composites, is that they "...can't relate to in-service material because neither the fracture appearance nor the amount of energy absorbed can be related quantitatively to the applied design" [Knott 1983].

For example, strain energy release rates, Gcrit, from linear elastic fracture mechanics, have been correlated with the impact damage of composites and resins [Halpin undtd]. However, while these values (used to describe the materials toughness in Mode I and II tearing), as determined from Double Cantilever Beam-DCB (G_{IC}) and End Notch Flexure-ENF (G_{IIC}), are again of some value in screening materials, they fall short as a tool for the designer in developing design allowables for impact resistance of real structures.

The alternative for the designer is to use these tests along with impact tests such as the instrumented drop weight impact test, compression after impact, or the like, for material screening purposes with the additional (and costly) requirement of impact testing the full-scale structure. Clearly, these tests, particularly the instrumented drop weight tests, have provided valuable information and insight into impact failure mechanisms of composites, as have a variety of destructive and nondestructive evaluation techniques. These include experimental techniques such as ultrasonic C-scan (for evaluating damage extent with respect to failure modes such as delamination, matrix cracking, perforation), scanning electron microscopy (SEM), fractography, optical microscopy, acoustic emission, and others.

Nevertheless, the designer is still left with the need to conduct extensive *and* expensive tests on full-scale structures to answer the questions of how the structure will respond to various impact events in service. This, of course, not only adds significantly to the cost and time to complete the project, but also erodes the confidence of the customer in these materials by the inability to definitively answer these questions. To underscore this challenge the "all composite" Beech Starship, certified in 1988 by the FAA, required 160 impact panel tests [Abbott 1989]. While the fact of certification is

itself a victory for the use of composites as primary structures, the costs were significant, and the assumption of future success in other applications is not valid. Impact properties, damage tolerance, durability, damage detectability, and damage assessment remain at the heart of the problem.

2.2.2 Predicting and Analyzing Impact Damage

Besides experimental methods for characterizing the impact behavior of composites, a number of workers have incorporated analytical and numerical techniques to evaluate the initiation and propagation of damage in composite plates. Many of the analyses have used finite element techniques with idealized boundary conditions and no preload; however, despite the simplified approaches, these analyses have proved invaluable to the understanding of failure mechanisms in composite laminates subject to impact [Grady 1986, Zukas 1982]. It seems likely that as computational techniques become easier to use and at the same time more powerful they will be invaluable design tools complementing experimental techniques in the resolution of the impact-resistant design challenge.

Certainly, current impact test and analysis methods are inadequate as design tools. Nevertheless, for design, as Sun [1989b] noted, exact solutions don't make sense; approximations are good enough. It is with this notion in mind that one of the thrusts of the impact design problem can be identified, i.e., develop design tools that assist the designer *now* with available techniques, heuristics, and knowledge while continuing the fundamental studies to advance understanding of the mechanisms involved in impact damage initiation, propagation and prediction.

As noted by Wolf Elber, Director of the U.S. Army Structures Laboratory, "With composites, clumsy handling may result in not just a dent, but the part becoming completely unusable." These issues—multiple impacts, and handling damage in real composite structures—are among the real issues with which the designer must grapple when attempting to define the impact requirements, predict the impact history of a structure, and design the structure given all the other design requirements.

2.2.3 Summary of the Impact Design Challenges

It is the complexity of real structures and the uncertainty of the impact event which make designing for impact in composites difficult, with respect to translating meaningful analytical and/or laboratory data to the design lab.

In summary, the following challenges are seen as worthwhile efforts for the design of impact resistance in composite structures:

1) Develop a coherent and comprehensive impact design methodology for composite structures built on a common design framework, including impact-specific design tools—analytical and heuristic.

2) Improve our understanding of impact failure mechanisms.

3) Show how impact-resistant techniques are included in composite structure optimization.

4) Develop tests and analytical tools for predicting the effects of structure on impact damage and its effect on residual properties. Take full advantage of bı ı ͜oning CAE tools.

5) Standardize NDE and NDT methods for impact testing, damage assessment, and damage detection.

6) Construct a knowledge-based expert system for impact-resistant design.

The challenges are clear; however, much has already been done to enhance our understanding of low-velocity impact damage and to improve impact structures in terms of their ability to resist this type of damage. The focus of this thesis is on items 1), 3), and 4).

Because of the complexity and uncertainty of the impact event and the associated structural response, a coherent and comprehensive design methodology which recognizes these factors is desirable. In the following section we will discuss some of the design methodologies proposed for composite structures, discuss their capabilities and limitations, and indicate how they might be used in the context of a structural design where impact resistance is an important design criterion.

2.3 Impact Design Methodologies

The Engineering Method is the strategy for causing the best change in a poorly understood or uncertain situation within the available resources.

Koen [1985]

2.3.1 Design Methodologies—An Overview

The literature has no shortage of design approaches or methods, which have varying degrees of utility in considering impact issues. They may be generally

categorized as 1) philosophical or universal, 2) industry specific, and 3) application specific, or 4) some combination of the above.

Sjoblom [1987] for instance, describes a simplified low-velocity impact design approach in which he presents a "global view" of impact. This approach is instructive in that it graphically depicts the interactions of the various structural levels (lamina to component) and impact event variables described above.

An application-specific design approach is formulated by Nolet and Sandusky [1986] for an improved impact-resistant leading edge design for the Air Force/Fairchild A-10 Thunderbolt II aircraft. Problematic bird strikes causing serious leading edge damage were the driving motivation for a better design. While this design approach is outside the realm of low-velocity impact problems and non-visible damage, it nonetheless, synthesizes various aspects of the design tools which will be discussed shortly.

How best to take advantage of composites in a design is not a new question. A design approach for the integration of composites into aircraft design was presented by Waddoups, et al. [1972]; and, while many of the issues have changed since then, it is still a matter of taking full advantage of the inherent properties of these materials in terms of freedom of structural configuration and integrity, manufacturability, and supportability.

Certainly, structural simplicity is a potential benefit of composites over metals and generally complements impact resistance. However, other desirable properties such as high stiffness may require tradeoffs if designing for impact (as with any "design for" consideration) is important. The important point of an integrated,

concurrent, or simultaneous design methodology is evident in Waddoups' conclusion, as valid today as it was then was that the biggest payoffs occur when composites are integrated into the design early in the product development cycle. To make full use of the greatly improved strength and stiffness of composites, new ways of thinking and new design approaches are required: simplicity is particularly important. The notion of integrating composites early in the product development process is as important for considering the vulnerabilities of composites as for taking full benefit of their strengths. In short, the critical identification, assessment, and evaluation of the customer's requirements and performance specifications early in the process will assure that critical design requirements are emphasized and that the best design solutions are formulated.

It is clear that impact should be considered in context, i.e., in the environment and under the design constraints of the particular application. In a sense, then, an application-specific approach should be employed to assure that the critical requirements for a particular application are correlated with meaningful and measurable engineering characteristics. Tradeoffs between engineering characteristics and their corresponding technical objectives are then evaluated to optimize the design.

We will discuss and critique some of the general design approaches and make the connection with "design for" impact issues.

2.3.2 Tsai's Integrated Framework for Composites Design

As noted in the introduction of this section, impact design approaches can be grouped into a number of categories. Despite the approach chosen, the trick seems to be to use one which is simple to understand yet sophisticated and thorough enough to treat

the particular design problem. Tsai [1988] suggests an integrated framework for composites design which is "...conceptually simple and analytically proper."

This approach links constitutive and environmental characteristics to laminate and structural behavior through the use of hygrothermal analysis and data, and micromechanical and macromechanical "bridges." Its primary strengths are simple yet powerful microcomputer-based analysis tools for materials, stiffness, and strength optimization of laminated composite structure subject to multiple combined *in-plane* loads. Excellent documentation accompanies the software, providing the theoretical underpinnings and the analytical approach.

As Tsai himself notes, it is not all-inclusive; in fact, "...the methodology in this book represents the minimum required." Of interest to the impact design issue is that it does not treat out-of-plane loads and could, in fact, lead the less than meticulous designer to a composite laminate design that is flawed with respect to impact resistance. Therefore, it may be useful to consider the Tsai approach as a specific set of tools, which combined with other approaches including impact design tools, may lead to a better composites design solution.

2.3.3 Sjoblom's Global View of Low-Velocity Impact

As a general methodology, Sjoblom [1987] treats the impact problem from a global point of view. On inspection, it is apparent that, even though Sjoblom's approach is presented strictly in the context of low-velocity impact design, the notion of correlating principal material and structural variables with structural response underlies the approach in the same manner as Tsai's.

Figure 2.1 depicts Sjoblom's global view of impact modified with feedback loops for refinement or optimization of the design. The important feature of this model is that it seems to include all the important material and structural interactions in the impact "equation." Determining which are the critical ones, identifying correlations, testing or analyzing their influence, and predicting their effect is the crux of the impact design challenge. Of course, this should be done in the context of real, often conflicting, design constraints.

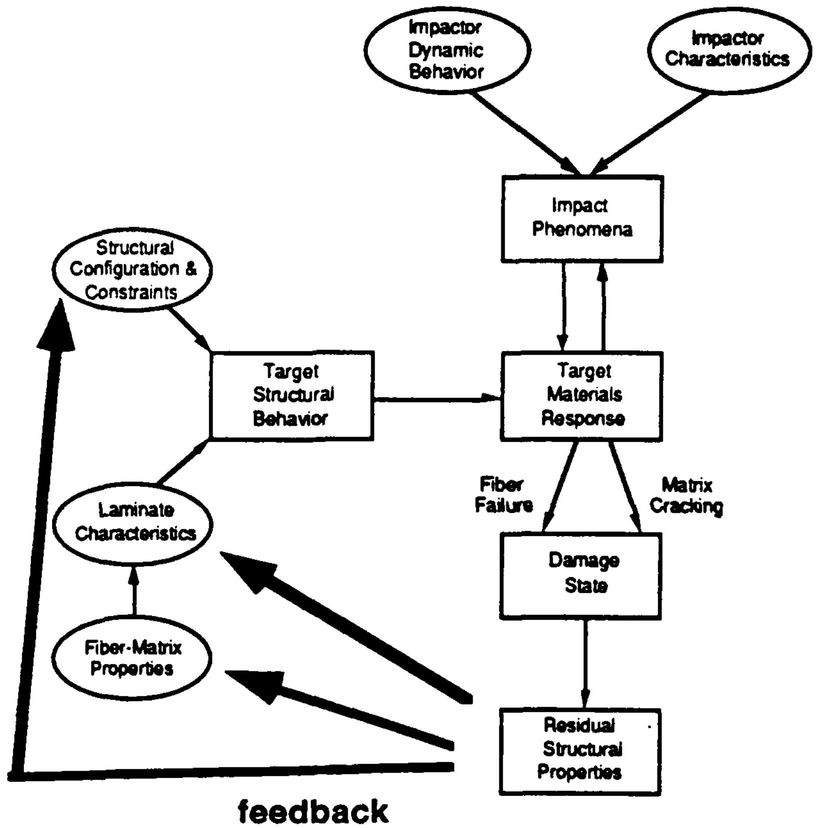

Figure 2.1. This "global view of impact" includes all the structural elements, impact elements, their interactions, and responses [Sjoblom 1987].

One might surmise that these correlations, particularly where they are in conflict, are extremely important for the designer in making appropriate tradeoffs. On the other hand, where the correlation is positive a synergistic effect may result.

It cannot, however, be considered complete as a design methodology, as it does not offer a vehicle for incorporating this model into a more general design approach involving other "design for" considerations and constraints of real structures.

2.3.4 The Improved Product Development Process—A Universal Approach for Impact-Resistant Design of Composites

The preceding discussion suggests that a more universal design approach might be appropriate for tackling the impact design problem. This approach considers all of the performance requirements (including impact resistance) and applicable quality metrics, correlates them, and determines the relative importance of each. Furthermore, it considers existing designs, and benchmarks them as needed to effect improvements. *Competitive benchmarking* is a good source of the heuristics and technology assessment which helps the designer make evolutionary improvements to products or systems while at the same time borrowing from the best efforts of others [Henshaw 1989].

The key to this universal design approach is listening to and understanding the customers' needs, translating them into performance objectives, and focusing on those critical design parameters which will most influence the success of the design.

Returning to the discussion of the historical development of high-performance composites for aircraft secondary structures, it is apparent that impact resistance as a critical design parameter was considered only after it became apparent that low-velocity impacts created severe delaminations which degraded the residual

compressive strength of the structure. At this point design fixes had to be employed at predictable cost. The initial promise of ever-higher specific stiffness and in-plane strength "blinded" composites designers to the corresponding vulnerability of these structures to insidious impact damage. The subsequent discovery of this damage in testing, in-service, and real manufacturing environments spawned a resurgence of damage-tolerant design approaches.

The lessons learned lead one to the general conclusion that a design tool is necessary to assure that critical requirements are identified and correlated with performance objectives and that requisite design tradeoffs are made. In the case of impact resistance, this may mean trading off in-plane properties, manufacturing costs, or other "design for" variables to meet an acceptable durability or damage-tolerance specification. The discussion of a tool which can treat "design for" impact requirements in the context of a global design approach follows.

2.3.4.1 House of Quality—A Concurrent Engineering Tool

A useful general approach to product development and design which focuses on the customer and, through appropriate discipline, leads the designer to a concentrated effort on the critical design parameters is presented by Hauser and Clausing [1988]. Termed the *Improved Product Development Process*, it uses a so-called *House of Quality* to satisfy critical customer requirements and employs Total Quality Management (TQM) philosophy and concurrent engineering to focus on the customer's wants (CW).

The beauty of this approach is its applicability to the development of any system, product, or service where a customer(s)-supplier relationship exists. What this has to do with "designing for" impact resistance in composites is simple—if, through

the implementation of the House of Quality, it is discovered that impact resistance is a required characteristic of the product then the other impact design tools at the designer's disposal would be employed to design for this characteristic.

The House of Quality is the logical starting point for *any* design project. It forces a concurrent engineering approach to design, requiring the designer to simultaneously consider competing design requirements. A cookbook approach for implementing the House of Quality can be found in King's *Better Designs in Half the Time* [King 1988].

2.3.4.2 The Pugh Concept Selection Process

The *Pugh Concept Selection Process* [Pugh 1981] is a useful tool for qualitative comparison of competing concepts with the benchmark, concepts which have been developed with the help of the House of Quality.

The efficacy of these and other product development tools for composites design and manufacturing was demonstrated by Henshaw [1989] in a folding composite bike design and an injection molded short-fiber-reinforced electrical connector preliminary design study.

Preliminary design concepts for products ranging from a composite prosthetic hip replacement to an elevator car to a composite sailboat winch handle have been developed. In each case the front-end effort involving market research, development of customer lists and customer attributes, and benchmarking the competition proved to be significant. When these tasks were properly and thoroughly accomplished, implementation of the House of Quality and Pugh Concept Selection

Process focused the product development teams on a better understanding of the critical design parameters and preliminary design concepts, respectively.

2.3.6 The Building-Block Approach to Damage-Tolerant Design

The building-block design approach—in which specimens representing critical areas are tested in various environments and where the specimen complexity and size vary from small coupons to elements, element combinations, components and large size structures—is common for structural design development. If damage-tolerant performance is required, then these same tests must be conducted on damaged specimens. Normally, the extent of damage and either the post-damage static strength or the life and residual strength is determined [Demuts 1989]. Only data obtained from the full-scale structure tests is useful for design purposes. Features of the building-block approach are also discussed by others [Kedward 1989, Lincoln undtd, Wilkins 1988]. It is the approach used when damage tolerance (e.g., safety of flight) issues are critical, as it culminates in full-scale structural tests.

Undoubtedly, this approach provides the most comprehensive information concerning the damage tolerance of a composite structure but at prohibitive cost for applications other than the most performance-oriented, where cost is less important than performance, e.g., fighter aircraft. Nevertheless, as fiber and matrix systems improve and less costly fabrication methods are developed, these testing costs are likely to be offset and will further motivate the shift from metals to composites in lower performance/high-production rate applications, such as automobiles and commercial aircraft. Cost is clearly motivating the development of predictive micromechanics and structural models for damage tolerance to obviate full-scale structural tests.

The building-block approach was deployed by Boeing and Northrop in a four-year program to develop a methodology for determining the damage tolerance of composite structures [McCarty 1986]. The key elements of the program were to

1) define damage tolerance requirements for composite aircraft structures,

2) investigate methods to improve structural damage tolerance characteristics,

3) demonstrate a building-block approach to damage-tolerant structure qualification, and

4) develop analysis methods for damage tolerance.

Damage assumptions were made for impact damage, i.e., "...assume the presence of damage caused by the impact of a 1.0-in.-diameter hemispherical impactor with 100 ft-lb of kinetic energy (energy cut-off) or the kinetic energy required to cause a dent of 0.10 in. deep (visibility cut-off), whichever is least." (Manufacturing-induced flaws and delaminations were also considered but these will not be discussed.) The analysis development sequence was developed from the impact energy requirement through various steps to a "residual strength combined analysis." Testing was conducted sequentially in a building-block test approach from coupon to panel to substructural 3-stringer panel and 5-stringer panel to full-scale box for determining critical damage under a variety of loading conditions.

Among the variables evaluated which affected impact resistance were 1) hard versus soft skins, 2) stitching, and 3) multiple impact damage. Thermoplastic (PEEK)-

and thermoset-matrix composite systems were evaluated. Results for the carbon/epoxy system demonstrated that skin hardness and stitching both had a significant effect on damage tolerance. Multiple impact damage, however, had a small effect [McCarty 1986]. In evaluating the thermoplastic-matrix system AS4/PEEK (APC-2), the Boeing team concluded that the system was tougher than the carbon/epoxy system because of reduced damage size (C-scan delamination areal measurement) and higher residual strength (compression after impact). Finally, an initial analysis method for the impact damage and residual strength prediction of composite material structure was advanced.

The objective was to form the foundation for the analysis of impact damage and develop an expanded analysis capability for a broad range of composite materials and structural arrangements. The method would

1) be adaptable to both current and future resin matrix and continuous fiber composite material systems,

2) include flat panels of any orientation and stacking sequence,

3) include damage to the resin matrix with no fiber failure accountability,

4) use failure strains derived from measurements on damage specimens, and

5) use failure predictions for the basis of property modification in the residual strength analysis.

This analytical model falls short of predicting composite material systems behavior in real structures under real environments and loading conditions yet provides a foundation upon which more comprehensive models may be built.

Using an impact-damage scenario, impact events are depicted on the load vs. time or deflection curve during the impact event. Figures 2.2 and 2.3 show the typical material response of a brittle epoxy system and a thermoplastic resin system, respectively.

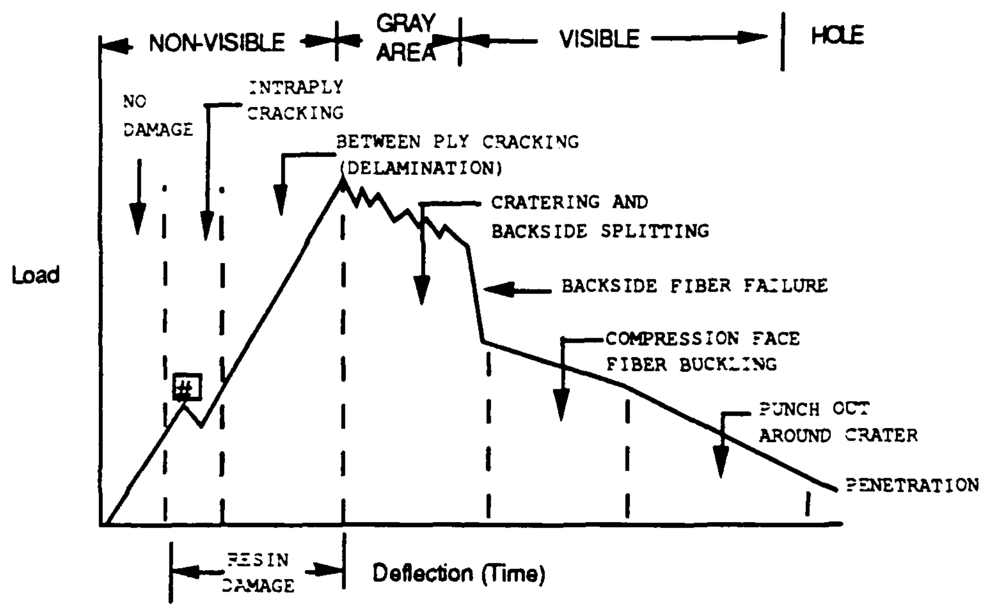

Figure 2.2. A brittle AS4/3501-6 composite laminate subjected to impact loading showing the regions and types of typical damage [McCarty 1986]. (The linear elastic region where non-visible insidious damage is developing is of paramount concern to the designer's predictions of residual strength and damage tolerance. The ability to visually detect the damage may be a function of location on the structure as well as material properties and impact energy. Note the low load levels at which incipient damage occurs—designated by #— in the non-visible region.)

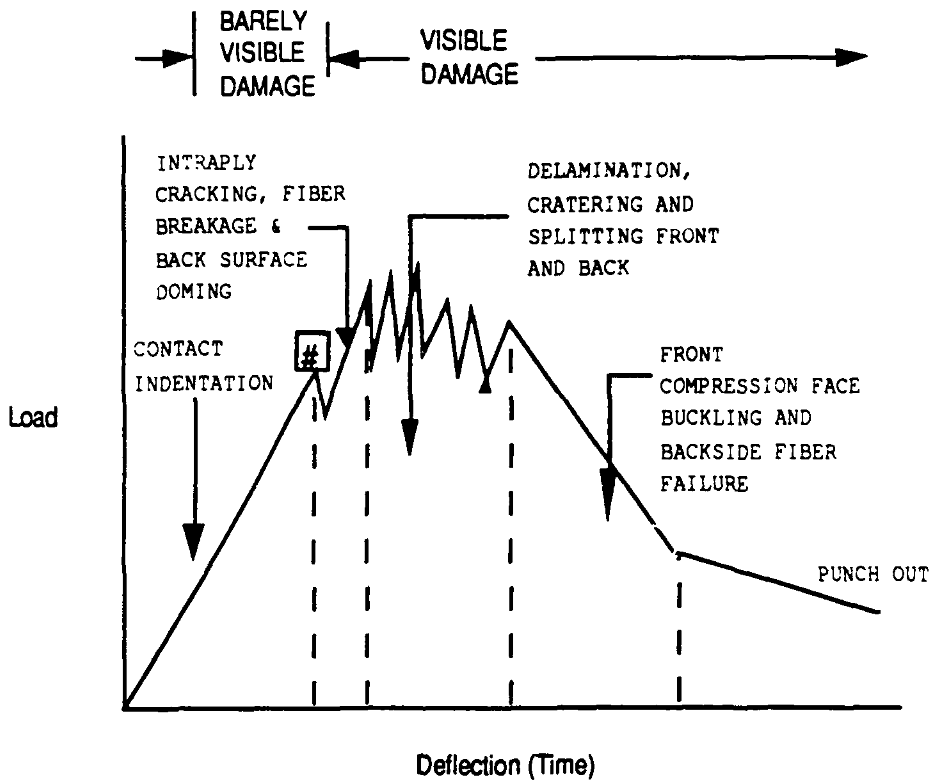

Figure 2.3 A toughened thermoplastic matrix composite laminate subjected to impact loading. (In these systems contact deformation is likely visible before the incipient damage point, #. It is desirable in low-velocity impact designs to delay the onset of microcracking and delamination, to narrow the bandwidth of the non-visible and barely visible damage zone, and to increase the area under load-deflection curve, particularly the linear portion.)

Correspondingly, Figure 2.4 is a through-the-thickness pictorial representation of the types of damage represented on the curve typical of a brittle epoxy resin composite.

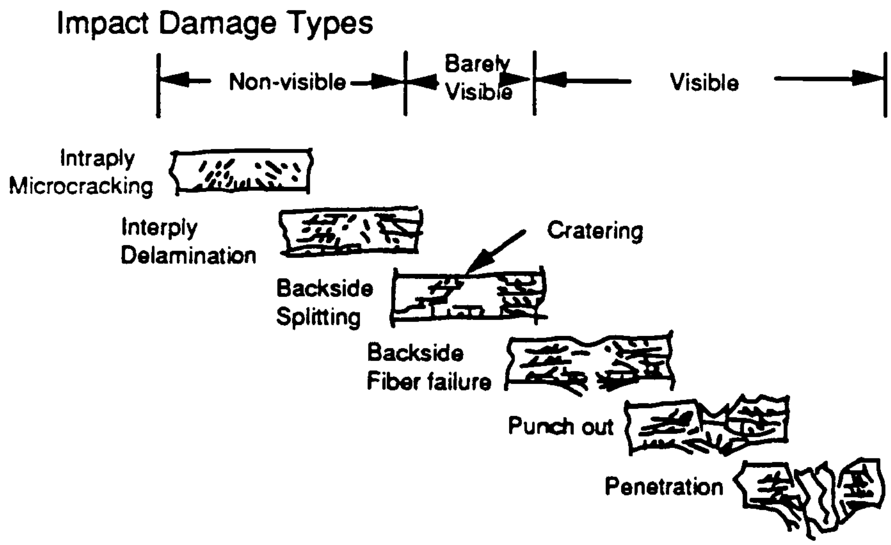

Figure 2.4. Typical damage progression in a "brittle" composite laminate.

The load-displacement curves, typically provided by instrumented impact testing, show the initiation and development of damage in composite material systems yet fail to account for all of the means in which real structures contribute to energy absorption and dissipation, thus, impact resistance.

Likewise, the analysis of simply supported orthotropic plates subject to low-velocity impact loads shown by Boeing uses simplifying assumptions which preclude their use as tools. Boeing concluded that 1) low-velocity impact can be analyzed using plate theory, including transverse shear coupled with Hertzian law of contact, and 2)

transverse shear failure of the matrix and interply delamination are the dominant failure modes for these panels. These conclusions would not generally apply outside the context of this analysis, limiting their use to the designer.

The building-block approach to designing for impact is typically used for specific applications with a limited number of control variables to be considered. It is apparent that, even in the Boeing case—evaluating two material systems and one stiffener design (I-stiffener)—the test program and required equipment, personnel, and dollars to support it became extensive. Nevertheless, within certain constraints and at later stages in product development, this type of approach may be necessary given the paucity of design data and the required level of confidence that these structures have to demonstrate with respect to damage tolerance.

2.3.6 Future Directions for Design Methodologies

Thus far the discussion has focused on design methodologies in general, in which impact is a design consideration. The major obstacle seems to be understanding the impact event well enough to be able to predict failure mechanisms, damage states, and residual properties of these materials and structures subject to impact loading. A secondary concern is evaluating alternative design approaches for optimizing these structures with respect to impact and other design requirements.

The use of a general product development methodology such as the House of Quality to identify critical impact design parameters, in conjunction with Sjoblom's philosophy of a global view of impact—coupled with satisfactory experimental, numerical and analytical tools—will facilitate the designer's ability to treat impact design issues in a thorough and efficacious manner. The need to reduce the scope of full-scale

structure testing through the development of effective modeling tools and predictive impact or equivalent quasi-static load tests is still a major challenge, as evidenced by the general acceptance and use of the building-block approach to damage-tolerant designs.

In Chapter 3 the author will outline a coherent and comprehensive impact-resistant design methodology which incorporates the best features and philosophies of those discussed above. It will demonstrate, given the current state of the art, how impact criteria can be considered early in the design process along with other "design for" "ilities."

2.4 Understanding Impact Failure Mechanisms in Polymer-Matrix Composites

2.4.1 Overview

The complexity of failure modes in impact-damaged composites is well documented; understanding of the micromechanics is much less so. The influence of fiber, matrix, fiber/matrix interface, lamina properties, laminate properties, structure, preload, and environment can all be significant in determining the type and sequence of failure modes as well as the extent of resultant damage (which of course influences the residual strength in which the designer is usually interested).

The end-product application determines which types of failure modes and damage are desired and/or acceptable. This is particularly important in terms of optimizing microstructure as well as macrostructure, to tailor specific energy absorption and dissipation mechanisms.

Figures 2.2 and 2.3 show that during impact loading the composite structure goes through stages of damage initiation (intraply microcracking), damage propagation (interply delamination), and eventually penetration, if energies are high enough. Of primary interest to the designer is predicting the onset of damage (incipient damage point) in the form of microcracking and delamination (in the linear portion of this curve) and its effect on the residual strength of the structure. The questions one needs to answer for a given set of impact parameters and conditions on a given composite structure are

1) How much energy goes into the initiation and development of damage and what are the failure modes?

2) Does the damage result in residual properties below design allowables?

3) Will the damage grow as a result of normal in-service loading conditions or subsequent impact events?

4) Can I detect or stop the damage growth before it exceeds design allowables?

5) Can I repair the damage?

6) Can I make quantitative predictions of the above by a test or analytical procedure?

The answers to these questions depend, in large part, on the predominant damage mode activated during impact. The extent to which any one damage mode predominates depends on the material properties, on the geometry or structural form,

and on the loading conditions. At relatively low velocity, bending can occur, and no damage results if the energy of impact can be accommodated by the elastic strain energy of the laminate. The critical condition exists when local stress exceeds local strength.

2.4.2 Delamination

Interply delamination is generally thought of as the most prevalent life-limiting failure mode in composites; therefore, it is a fundamental issue in evaluating the impact resistance or, more generally, the durability and damage tolerance of composites. Consequently, a number of workers have focused on developing an understanding of delamination and its importance to design through a variety of analytical, experimental and modeling techniques [Browning 1984, Elber 1983, Bostaph 1982, Bostaph undtd, Clark 1989, Dow 1988, Gandhe 1989, Gosse 1988, Grady 1986, 1987].

Garg [1988] has written a comprehensive review of delamination failure modes in composites, highlighting causes (including impact) and effects on residual strength and discussing methods of suppressing delamination such as improved resins, through-the-thickness reinforcement, and interleafing. Design considerations such as "discrete-stiffness design" and mechanical fastening as a way of arresting the propagating damage are described. Also discussed is the prediction of delamination behavior by calculating interlaminar stresses, σ_z,[1] or onset of delamination via either a

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1Pagano and Pipes [Pagano 73] developed an approximate solution for the normal component on interlaminar stress state which could be used to give a good idea of delamination [impact] resistant stacking sequences based on approximate σ_z distribution.

fracture mechanics approach [O'Brien 1982, 1984, 1985] or strength of materials approach [Lagace 1986].

Interlaminar fracture toughness, a delamination critical property, can be evaluated by DCB (G_{Ic}), ENF (G_{IIc}), Crack Lap Shear-CLS (Mode I and II) and Edge Delamination Tension-EDT (total Mode I and II) and Split Cantilever Beam-SCB (G_{IIIc}), for graphite-epoxy systems. Others have used these tests for evaluating toughness in toughened matrix composites [Browning 1984, Kam 1987], thermoplastic systems, and for woven or braided structures [Verpost 1989] where the assumption of linear elasticity may not be valid. Browning [1984] concludes that the DCB test is a useful "screening tool" for determining approaches to improve delamination resistance.

The conclusions Garg draws from this paper with respect to delamination are as follows:

1) Delamination is an important damage mode which may not be surface visible but can affect strength and stiffness.

2) Delamination may not deteriorate in-plane tensile behavior, but it seriously degrades compressive strength.

3) The root cause of delamination is poor interlaminar toughness, which may be improved by some of the methods mentioned above.

4) Predicting the onset of delamination is computationally extensive. A simpler method is needed.

Predictably, considerable emphasis has been focused on the development of methods and techniques to prevent delamination. Most of the effort has been toward

improving the toughness of the resin [Evans 1987, Griffin 1987, Klein 1988a & b, Lee 1986, Murri undtd, Wedgewood 1988, Stinchcomb 1989, Wedgewood 1988] or in using techniques such as interleafing [Elber 1978, Gandhe 1989, Masters 1986, 1987b, Seferis 1989, Hirschbuehler 1985] to increase interlaminar shear strength and Modes I and II strain energy release rate. Other techniques use novel mechanical approaches to contain damage or arrest it. These include tear strips, adhesive strips [Sun 1989a], buffer strips, stitching [McCarty 1986, Ogo 1987], and weaving techniques [Cantwell 1983, Fang 1988] and will be commented on later.

As Sun [1989b] points out, these techniques are not a panacea for impact damage problems. There is, he admonishes, "no free lunch" in that while tougher resins and interleafing may suppress Modes I and II failure, the energy of the impact event must go somewhere. (The best impact design would absorb energy in linear-elastic mechanisms.) At higher velocities and energies, if delamination is precluded as a failure mechanism due to the suppression of Modes I and II failure, then other failure modes come into play, such as fiber breakage, which may result in more damage and poorer residual properties than with the "brittle" matrix system. The lesson from this is that the use of these "toughening" interleafs and resins should be considered in the context of the application, impact threats, and the manner in which these methods change the failure modes and the damage development process.

2.4.3 Microcracking

While much effort has been devoted to describing interlaminar shear failure modes and gross delamination (the type described above—those greater than two-ply thicknesses in length) of composites in low-velocity impact, Rogers [1989a] and others have described a primary initial failure mode in low-velocity impact and other loading

situations as a form of *microcracking*. Rogers defines microcracking as a crack approximately one-ply thickness in length, either matrix or fiber failure, which reduces local stiffness and changes the load path, resulting in gross delaminations and, finally, fiber failure in tension or compression, or sublaminate buckling under compression shear or flexural loading. Microcracking becomes visible as color changes, crazing, surface cracks or broken fibers. Of the seven types of matrix microcracking and two types of micro-fiber failure defined by Rogers and identified by others, shear cracking, a type of transverse tension cracking at 45° to the plane of the ply (Figure 2.5) occurs at impact sites and is due to out-of-plane shear loads.

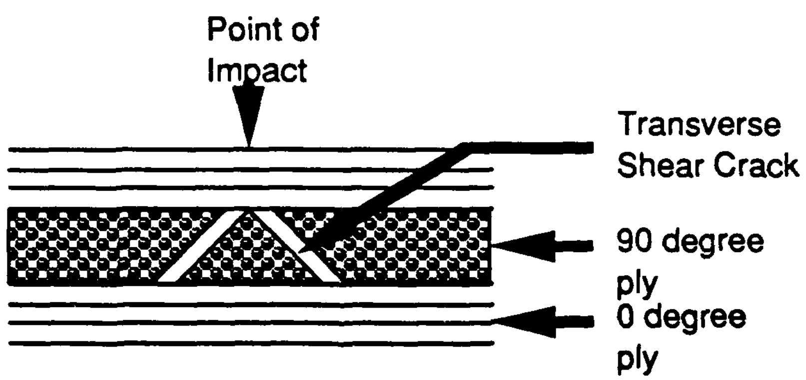

Figure 2.5 Transverse shear microcracking in 90° ply impact induced (after Rogers [1989a]).

The shear strain is due to very local deformations resulting from the dynamic loading of impact. One observation of interest is that it also occurs where local out-of-plane deformation is induced by static loading. This suggests the possibility of

predicting impact response using static loading methods.[1] Following from the shear crack is a micro-delamination which initiates at the intersection of a shear crack (or transverse tension crack) and an adjacent laminae surface. It can also form at ply terminations.

Transverse intraply tensile microcracks are also observed in impact coupons in plies at or near the back surface or on the periphery of the impact surface contact zone, suggesting a critical matrix strain value as a failure criterion, ε_{90°. This type of failure mode is predictable [Zukas 1982] where plate bending predominates and will be characterized in Chapter 6.

The so-called "gross delaminations" discussed previously grow from micro-delaminations or result from delaminations created by impact. The gross delaminations can be detected by many methods and are considered failure requiring repair or replacement. While this failure may represent a nonresilient or nonimpact-resistant behavior, it could provide adequate damage tolerance depending on how the part is loaded. The progression of microcracking in in-plane shear has been described by O'Brien [1982]. According to Rogers, microcracking develops randomly at very low strain levels; it can be benign and beneficial. The description of another type of microcracking, a split (Figure 2.6) aligned with load and initiated at the side of a hole or discontinuity, is both benign and beneficial.

The system should allow this phenomenon to occur. In some cases, where tougher resins have been promoted by material developers to improve impact resistance,

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[1] This, indeed, has been demonstrated to be a valid approach by Elber [1983] for low-velocity impact events and is investigated in the author's research, Chapters 6 and 7

in terms of compression after impact strength, this has been accomplished at the expense of open hole strength. Understanding these related issues is necessary to optimize both properties, thus providing both impact resistance and damage-tolerant qualities.

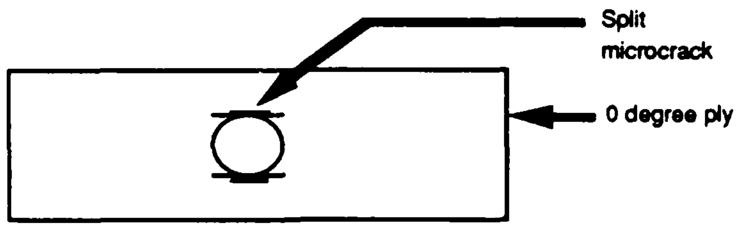

Figure 2.6 An impact-induced split microcrack occurring tangential to the hole (after Rogers [1989a]).

Rogers [1989a] notes that material developers should be guided by two goals: 1) delaying the onset of shear strain microcracking, and then 2) increasing the energy level required for delaminations, achieved by: 1) a slightly tougher resin and a slightly higher resin content to delay the onset of shear microcracking, and 2) interleafing to improve interface toughness through thin films or thermoplastic spheres. The drive toward minimum resin content and thicker plies/ply groups contributes to low impact resistance. The theoretical underpinning of the effects of thickness can be summed up as follows, "The strain required to initiate a transverse crack is greater when the transverse lamina is thinner, in some cases cracking is constrained completely up to the strain at which longitudinal lamina fail catastrophically," Chou [1989]. In short, in order for a crack to form it must be both mechanistically possible and energetically favorable.

2.4.4 Other Impact Failure Modes

Other impact failure mechanisms—cratering and splitting on the front and back side, front compression face buckling, backside fiber failure, and punch out—normally follow microcracking and delamination. They tend to be barely visible or visible failure modes occurring at higher energy levels. In most cases, these types of failure modes will require immediate repair, but if safety of operation is a design criterion, the part must meet the damage-tolerance requirements for continued operation until repair or replacement can be effected.

As noted, in very tough resin systems with high failure strains, delamination failure modes are inhibited, and fiber breakage may be the predominant failure mode. For higher impact energy levels this could result in a less damage-tolerant system with lower residual strengths in both tension and compression as compared with a more brittle matrix system, in which delamination predominates and, thus, serves as a major energy absorbing mechanism.

It is clear that a myriad of failure modes can exist as a result of an impact event depending on the material system, impactor properties and velocity, structural configuration, and loading conditions [Dorey 1984]. Understanding the interaction and effect of each of these on the other and controlling them will allow one to get the desired performance from the structure. To accomplish this, knowledge of the structure's influence on local failure modes is essential. Development and execution of a design methodology, including an effective testing method, is needed to facilitate decision-making regarding impact-resistant designs. Much of the work described here and by others has gone a long way toward providing the scientific and engineering foundation required to make this possible and has motivated the direction of the author's research.

2.5 Instrumented Impact Testing

With a sound and fundamental understanding of the failure modes, improvements in impact performance can be "designed in," starting with the properties of the constitutive materials, through the laminate properties, to the structural configuration and constraints. Each of these interact to produce the target material response and, ultimately, the damage state. One of the inherent difficulties, as mentioned previously, in describing impact failure modes in composites has been in the development of appropriate and standardized test methods to screen materials and to predict their impact performance in-service. Charpy and Izod impact tests, routinely used for characterizing impact properties of isotropic materials [Matthews 1970], have proven inadequate for impact testing anisotropic composites and have largely been replaced by drop weight or pendulum instrumented impact test methods—which provide greater insight into specimen response throughout, including failure mechanisms—and compression after impact tests for residual strength measurements.

The instrumented impact testing method has allowed workers to partition the impact event (Figure 2.7) into different regions as a function of load vs. time (displacement).

The amount of absorbed energy corresponding to impact events identified on this curve can also be determined. Toland described these regions as pre-initial failure, initial fracture and post-initial fracture, and has used them to relate fracture behavior to fundamental failure modes. This type of testing method allows workers to “creep” up on the initial fracture by reproducing tests at energies below that required for the initial fracture.

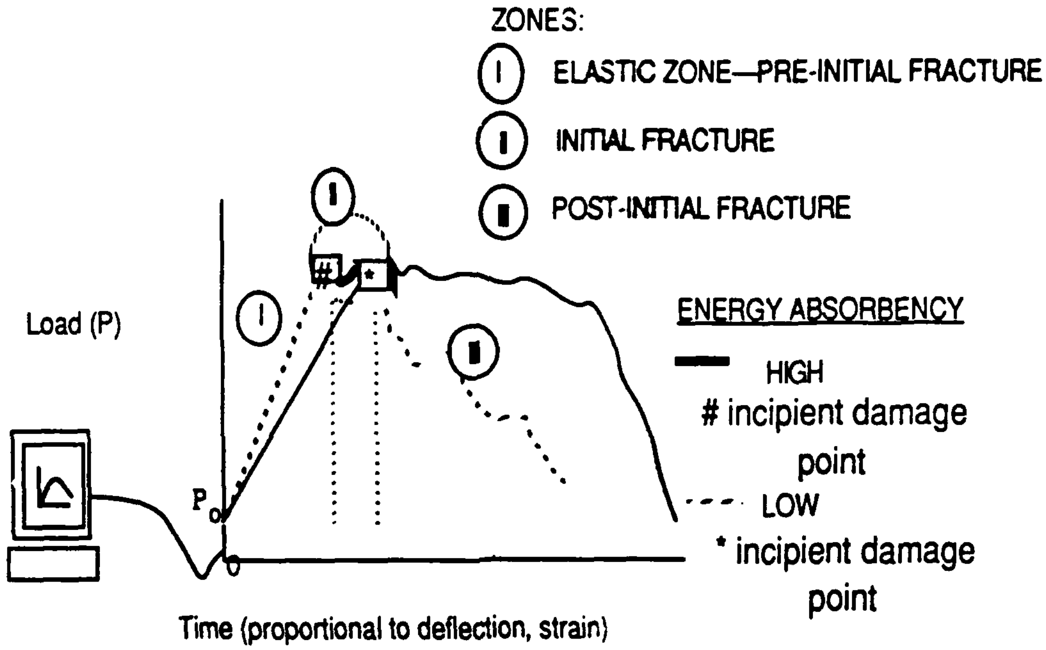

Figure 2.7 Load-Time curve as measured by instrumented impact test equipment (after Toland [1973]). The author believes the critical point in this trace, from a design perspective, is the incipient damage point.

This is much more revealing than traditional methods, which simply give total energy to fracture (toughness) as determined by the difference in pre- and post-test potential energies of the impact tup. Cheresh and McMichael [1987] give a detailed primer on conducting instrumented impact tests and interpreting their results .

In the *pre-initial* fracture region (Figure 2.7) the behavior on a gross phenomena level is a function of the specimen compliance under the given dynamic load. Toland notes that "in three-point bending specimens, compliance is determined primarily by fiber elastic properties in tension and compression contributing to the

specimen and compliance in bending and the resin shear properties as contributing to the specimen compliance in shear."

For design purposes the load energy to initial fracture may be critical. Instrumented testing allows an effective method of identifying the incipient damage point, thus providing valuable design information to the designer, provided the structural influence of the test apparatus is known.

The toughness of the composite and its ability to absorb energy in the region three of Figure 2.7 depend on a number of factors. A lack of energy-absorbing ability could result in brittle type behavior, where the failure mode would be a cleavage type failure of both the matrix and fibers, whereas a large area under the load-displacement curve, would represent "ductile" type behavior. This can easily be shown as a function of the fiber strain to failure; however, other workers have also shown it to be a strong function of resin content, stacking sequence, and ply orientation. While this area may be of interest in ballistic impact damage tolerance and durability, it is of less relative importance in designing for low-velocity impact resistance where behavior in region one and the onset of damage in the matrix is of primary significance.

Clearly, instrumented impact testing gives one the capability to identify the precise loading conditions under which these failure modes occur; however, as noted, other simpler test techniques for achieving the strain allowable values may be equally effective.

It is well known that the designer can improve both impact resistance and damage tolerance through various energy-absorbing mechanisms such as fiber debonding, fiber pullout, and interply microdelamination (all toughening mechanisms).

Instrumented impact testing is a valuable tool for understanding and describing the occurrence of these events; however, the ability to use impact test results directly in designing structures has not yet been realized. Perhaps by gaining a better understanding of the influence of the test apparatus on the development of damage in composite test specimens, while simultaneously modeling and analyzing real structures for their influence on target response under impact loads, the designer may be able to compare the two and predict the material response and damage states under a variety of impact events.

2.6 Durability and Damage Tolerance

Thus far we have discussed damage tolerance and durability without formally defining them. Since one or the other of these is normally found in the customer attributes list for a particular design where impact resistance has a high relative importance, it is important that the designer have good working definitions. The user may provide specifications in terms of damage tolerance and durability requirements; thus, the nuance of difference between them is important as are the ramifications of these requirements for other "design for" requirements.

Durability is simply the ability of a target to resist damage for a specified period of time (MILSTD 1531). Service and handling impacts are the primary concerns for the designer. Low durability/impact resistance translates to increased frequency of repair and high maintenance costs. Good durability usually results from resin toughness and strength, structural flexibility, and resiliency (area under the elastic portion of the stress-strain curve). A composite design which moves the incipient damage point up the load-deflection curve improves its durability. Ideally, the durable composite is one in

which a large amount of energy may be absorbed before damage initiates and one in which damage is clearly evident through routine inspection well before it is critical. Economics is the bottom-line issue here in terms of cost of ownership of the article [Lincoln undtd].

Damage tolerance is the ability of a structure to resist failure in spite of the presence of flaws, cracks, or other failures for a specified period of time (MILSTD 1531). This is primarily a safety issue, and, unlike durability, it assumes damage already exists. Damage may be a result of process-induced flaws, manufacturing defects, in-service damage, etc. Damage-tolerant designs have the ability to stop delaminations or prevent gross delaminations. The development and investigation of damage containing adhesive strips for carbon/epoxy prepreg by Sun [1989a] is an excellent example of a damage-tolerant design approach at the lamina level. Other damage tolerant designs for material systems and structural components, i.e., those which control defects, will be highlighted in the next section.

The key assumption of a damage-tolerant design is that the damaged part will continue to function at some performance level at or above a specified level of safety: 1) for the service life or inspection interval of the part, 2) until the damage is detectable and can be repaired, or 3) for some specified number of missions or hours after the damage occurs and has been detected.

An example of damage tolerant design is the replacement of carbon

fiber/Kevlar-epoxy spar on the Sikorsky UH-60 helicopter with a more damage-tolerant/tougher PPS matrix composite part.[1] [Witzler 1989b].

"Designing in" damage tolerance is generally expensive and therefore should be limited to parts and structures for which it is absolutely necessary. Structures subject to impact-induced damage can be identified through the impact design methodology alluded to above.

Damage tolerance depends on the growth behavior of assumed existing flaws. The requirements for damage-tolerant designs should include

1) designing parts as non-inspectable structures,

2) assuming that non-visible damage is present, and

3) safely containing the damage for the entire life of the part.

For structural applications, designs must relate possible incidence of impact damage to its effect on performance [Dorey 1987].

2.7 Techniques for Improving Impact Resistance in Polymer-Matrix Composites

The literature is replete with a variety of techniques and methods which may be helpful in improving the impact resistance of composite structures. The following

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[1]PEEK was the first choice, but due to degradation of the KEVLAR fibers at the high processing temperatures of PEEK, an alternative matrix was needed.

discussion surveys some of the work done to develop the materials and techniques which have enhanced the impact resistance of composite material systems and structures. These will be viewed from a global perspective as proffered by Sjoblom.

2.7.1 Tough Matrices

Thermoplastics and toughened thermosets offer dramatic improvements in impact damage resistance[1] and damage detectability, particularly for low-velocity/low-energy impacts where suppression of microcracking and delamination is critical. The message to material developers has been clear. Users are demanding material systems which are stronger and stiffer yet still give good hot/wet high-temperature performance and offer resistance to corrosion and impact. Furthermore, these systems must be cost efficient with respect to manufacturing, ideally being reprocessible (as in the case of thermoplastics).

Besides CAI tests and C-scan measurements, linear elastic fracture mechanics measurements of strain energy release rates for Mode I and II (G_{Ic} and G_{IIc}) have been used in material screening and development to assess the toughness of a matrix system. These values tend to have more meaning for the brittle system where fracture occurs well below yield stress; and, thus, assumptions of linear elasticity are more likely to be valid.

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[1]These improvements were determined by compression-after-impact (CAI) residual strength [Lee 1986, Williams 1982] and C-scan damage zone. CAI strength measurements are often cited when describing the impact resistance or damage tolerance of a composite material system; however, the problems of analyzing and interpreting the results of these tests are well known. Their value in terms of predicting compressive behavior in real structures is doubtful.

In real situations damage initiation is controlled by the matrix strain, ε_m, or $\varepsilon_{90°}$. This critical value, ε_c, can be identified on the stress-strain curve at the point of deviation from linearity and, likely, coincides with the incipient damage point in the instrumented impact test.

2.7.1.1 Toughened Thermosets

Thermosetting matrices (epoxies, BMI's, phenolics, polyimides and the like) are brittle, solid, 3-D networks of highly disordered covalently bonded polymer molecules. This brittleness, or propensity toward linear elastic fracture at low strains, manifests itself in matrix cracking and delaminations under relatively low-velocity/low-energy impact loads such as those encountered in normal service and handling, e.g., tool drops, runway foreign object damage, and handling during manufacturing. The desire of the composites industry to improve the fracture toughness of epoxy resins has been the subject of a great deal of research in the past two decades and has resulted in a variety of tough thermoset-matrix composite materials despite the promise of thermoplastics for high performance applications where impact resistance is a critical design parameter Klein [1988a].

Since unmodified epoxies are brittle, they are often modified to improve their impact resistance to low-velocity impacts. Thermoplastic modifiers, e.g., polyaromatic and polyarylene ether sulfone, have been successfully added to epoxies to provide this added impact resistance. Unlike rubber particles, which are liquids at room temperatures, these thermoplastic polyarylene ether sulfone particles do not sacrifice modulus to achieve toughness. This new breed of epoxies is being developed to meet the demands of greater toughness, higher operating temperature, and ease of processing.

Tougher matrices usually provide improved interlaminar fracture toughness at the expense of hot/wet compression strength. These systems produce compression failure modes comprising fiber or ply buckling instabilities rather than delamination growth in carbon/epoxy. The changes in failure mode must be carefully considered, since improvements in some properties could result in degradation in others. This is not a trivial point for designers because failure modes determine design allowables, and the designer must understand how the impactor and impact event, the material system, and the structural configuration and constraints of the target affect the target response, thus the failure modes.

Among some of the newer entries in the thermoset-matrix market to challenge the epoxy standard are the polyimides which resist high temperature but are brittle, and bismaleimides (BMI) toughened with energy-absorbing rubber particles and exhibiting enhanced impact performance; however, the compression strength, modulus, and glass transition temperature of these toughened systems are all reduced considerably. Again, as in the case of the epoxies, thermoplastic particles such as polybenzimidazole are being added to BMI's to provide better compression and higher glass transition temperature, Tg, while enhancing impact resistance Klein [1988b].

It may be tempting to consider toughness as an inherent material property which it is always desirable to improve, in terms of G_{Ic} and G_{IIc}, for example; however, in evaluating the impact toughness of thermosets and thermoplastics Stinchcomb [1989] revealed that the better system, with respect to residual tensile strength under short-term impact loading, is the brittle thermoset system. This is due to the difference in failure modes of the two. The primary failure modes are fiber failure in thermoplastic [AS4/PEEK] systems and matrix cracking and delamination in the brittle

matrix systems [T300/5208 and AS4/3501]. The result is higher residual tensile strength in the epoxy systems under short-term impact loading; however, under long-term fatigue loading the reverse is true. Thus, the designer is enjoined to consider tradeoffs between these competing requirements.

Significant relative improvements in Modes I and II interlaminar fracture toughness of toughened resin systems over the brittle systems, determined by G_{Ic} (DCB) and G_{IIc} (ENF) measurements [Murri undtd], can be achieved. Depending upon the test variables, a wide range of conclusions has been reached regarding the effects of matrix (and fiber) toughness on measurable residual strength [Lee 1986, Griffin 1987, Owens 1989].

It seems likely that thermosets will continue to command the market share in prepregs (over 80% through the year 2000 has been projected). So while high-temperature thermoplastics may offer great promise for future high-tech applications, the designer will find real constraints in the near term with regard to these new materials' availability, characterization data, and cost. Furthermore, for the reason cited above, a standard thermoset system may often provide better performance under short-term impact loadings.

Techniques for getting the most impact resistance from currently available prepreg materials will be the near-term focus for product engineering and design, while resin suppliers will continue to strive for improvements in the toughness of their products to meet the extreme requirements of the user. This most certainly will affect the designer's ability to take fuller advantage of the in-plane properties and potential manufacturing efficiencies these systems offer. It should be kept in mind that design solutions may be as simple as the selective use of a prepreg with a higher resin content

or the use of an interleafing resin in vulnerable areas to achieve the desired impact resistance.

2.7.1.2 Thermoplastics

The other major category of matrix resins is the thermoplastics. Besides their oft touted promise for flexibility, ease of manufacturing, reprocessibility, and recyclability, these tough matrices have exhibited excellent impact resistance and damage detectability at relatively low energy (an important customer need). Furthermore, they promise to be relatively easy to repair and maintain, important considerations in any impact design.

The short list of material suppliers producing these resins, and their relatively high cost account for their limited use in the composites business thus far. (PEEK was first introduced in 1982 [McDermott 1990].) Nevertheless, this group of matrix materials, which includes liquid crystals, polyamides, polyamide-imides, polyarylene sulfides, polyetherimides, the polyetherketone family (PEK, PEKK, PEEK), some polyimides, and polyphenlylene sulfide, is a major focus of current research, development, and product design for the reasons cited above. Cost, immature manufacturing technology, high-temperature properties, and lack of material characterization and test data are some of the challenges for these matrix systems.

Polyetheretherketone (PEEK) matrix thermoplastic composites, such as ICI's AS4/PEEK (APC-2) investigated by Hines, et al., [1987] and Dorey, et al., [1985] showed excellent impact properties in comparison with carbon/epoxy. This is encouraging, given PEEK's high temperature capability, 350°C and low hygroscopicity—a problem with thermosets. One of the driving motivations for the use

of these resins is the excellent Modes I and II fracture toughness they have exhibited, which seems to be important in improving impact resistance.

Wedgewood [1988] has shown that at low impact energy levels, 6.67KJ/m, the mode of damage is predominantly matrix controlled—resin cracking, delamination, etc.—and the extent of damage is usually small when compared with the size of the structure. Thus, the residual properties are a strong function of resin toughness. At high energy levels, 13.34 KJ/m, failure modes are matrix and fiber controlled but appear to be independent of resin toughness. Wedgewood's work was conducted on high-temperature thermoplastic matrices and their composites using polyamide/ and polyimide/graphite systems. They also found that fracture surface topology suggests that fiber bridging and pullout are active energy dissipation mechanisms which improve interlaminar fracture toughness in resins with lower toughness.

Clemans and Hartness [1989] provides comparative data on PEEK, PEK, EKEKK, Larc-TPI, HTA (Polyether Sulfone), polyetherimide (amorphous and semi-crystalline), and polyimide (PMR-15, 2080, Matramide 9725). He concludes that the excellent mechanical properties including impact resistance, coupled with ease of processing, bode well for these matrices. In short, minimizing the low-velocity impact damage requires that the matrix have high strength and low modulus [Zukas 1982], the thermoplastics seem to meet these criteria nicely.

2.7.1.3 Interleafing

Modification of laminate interply mechanical properties via the introduction of a thin layer of resin, adhesive, or the like has proved fruitful in improving the composite properties generally associated with toughness. This process is commonly

called *interleafing* and has been shown to suppress impact-induced delamination and reduce matrix cracking [Hiel 1989, Amer Cyn 1987].

Interleafing has been shown to improve the impact resistance of carbon/epoxy and graphite/bismaleimide composite material systems. This improved impact resistance is typically manifested as an increase in residual strength in compression-after-impact testing. Interleafing alters the pattern of impact damage development. The result is only a nominal increase in G_{Ic} values, but the G_{IIc} values are significantly increased.

Interlayer resins must have a large ultimate shear strain and must remain a discrete layer after the laminate has been cured. Both thermosets and thermoplastics have been employed successfully as interlayers. A number of workers have investigated a variety of approaches which range from toughening of graphite-epoxy composites with discrete perforated interlaminar mylar films [Elber 1978]—designed to suppress delamination—to integral interlaminar damage containment strips [Sun 1989a]—designed to allow damage to occur up to a noncritical size with respect to design allowables for stiffness and strength.

Sun's solution, as mentioned, is damage containment, which he terms the *controlled damage concept*. The design tradeoff for laminate design using adhesive strips and softer adhesives is a loss of stiffness. To obviate this problem, Sun's controlled damage concept includes reinforcing these adhesive strips with fibers. He suggests that strip width and spacing can be optimized for a particular application. Tradeoffs in cost and manufacturing would eventuate; however, this technique, as is the case with many of these techniques, may be used optimally in impact-vulnerable locations.

Interleaf systems have suffered from poor high-temperature performance; however, improvements have been reported in this performance category by Hirschbuehler [1985] with a 270°F performance interleaf system.

As in the case of tough resins, Browning [1984], using the DCB test for interlaminar fracture toughness measurement, demonstrated that the incorporation of an adhesive in-lay, either by itself or in conjunction with a Kevlar mat, was extremely effective in increasing G_{Ic} values (delamination resistance).

Evans [1987] showed that the combination of new toughened epoxy resins with novel interleafing materials results in composites exceeding the ultimate design strain target of 0.006 cm/cm while providing a hot/wet compressive strength to reduce weight by over 40% compared to 2024-T3 aluminum. In addition, these improved interlayered systems have two other attractive features: 1) their residual compressive strengths after impact are comparable to those of thermoplastic matrix resin systems; and 2) they process and cure like standard epoxy materials.

The promise of interleafing in helping to solve damage tolerance problems has led to a concept by Seferis [1989] involving the incorporation of an integral interleaf resin layer during the prepreg manufacturing process. This could result in reduced costs to parts fabricators by obviating the placement of discrete interleaf layers.

The designer should consider selectively toughening the ply interfaces which delaminate under load, thus increasing the resistance to impact and decreasing delamination damage [Masters 1986, 1987b]. Semi-empirical models such as that presented by Gosse and Hause [1988] will allow the designer to predict, ply by ply,

delamination zones under low-velocity impact so that interleafs may be used to greatest effect from both a performance and a cost viewpoint.

2.7.2 Tougher Fibers

For fibers of interest to designers today, fiber stiffness, strength and interfacial properties are likely to be important parameters when assessing impact properties of the structure. Which of these or other properties are critical will depend on the expected failure mode of the composite subject to impact. This, of course, will likewise depend on matrix properties, structural configuration and constraint, stacking sequence, etc. For example, Greszczuk [Zukas 1982] reported that when the volume of the damage zone was used as a measure of impact resistance in flat quasi-isotropic composite plates, only local stresses and deformations needed to be considered. Under these conditions, ultrahigh-modulus Celion GY70 had the lowest impact resistance, while Thornel 300 (high strength, moderate modulus) had the highest in the unidirectional specimens. A significant amount of strain energy is stored in the fibers.

Toland [1973] suggests that the relative impact absorbing ability of fibers can be ranked by using the following expression:

$$U_f = \frac{1}{2}\sigma_f \varepsilon_f v_f \tag{1}$$

where U_f is the strain energy, σ_f the fiber tensile stress, ε_f the fiber tensile strain , and V_f the volume fraction of the fiber

On the basis of this equation, low-modulus, high-strength fibers should provide the greatest resiliency, particularly on the front and back surfaces where compression and tension stresses, respectively, are greatest.

The fiber reinforcements of major interest to the composites designer are graphite, boron, S or E glass, aromatic polyamides (aramids), and, recently, high strength polyethylene, Allied's Spectra™. These fibers can be used alone or in combination with one another to achieve the desired impact properties [Adams 1986]. Of course, other design requirements such as processing compatibility, high-temperature performance, etc., will play a part in the selection process. Other fiber properties such as vibration damping have been correlated with improved impact resistance [DuPont 1981].

The effectiveness of glass fibers in impact resistance, particularly when used in systems with relatively high volume fractions of resin (polyester or vinyl ester), has been recognized by the boating industry since the introduction of fiberglass hulls in production boats in 1956. The extreme marine environment and typically hard use to which these boats are subjected have resulted in experience-based designs that take full advantage of the properties of glass fibers yet keep production and tooling costs down. Recent developments in this industry have seen hybrids of glass, carbon and Kevlar fibers in boat hulls boasting of high stiffness, light weight, and excellent impact resistance. The high density of glass fibers is a drawback where weight is a driving design criterion, such as in the aerospace industry; however, the judicious use of glass in this industry, particularly where impact resistance and low cost are of concern, has proved fruitful [Scott 1988, Irving 1987].

Aramid fiber and, now, polyethylene offer excellent impact properties when used alone or in combination with graphite where a higher specific stiffness is required [Bugsen 1989]. However, both aramid fibers and polyethylene are poor in compression. In addition, highly oriented high-modulus polyethylene fibers are subject

to creep under constant load, and they have a low melting point [Hearle 1982]. These and other properties must be considered in designing an impact-resistant system.

The effectiveness of the aramids Kevlar 29, 49, and, now, 149 has been investigated by a number of workers, both alone [Miner undtd, O'Kane 1986, Wardle 1982] and in hybrids with carbon fibers [O'Kane 1986, Wardle 1982, Nolet 1986].

Wardle [1982], in investigating fibers for their impact resistance, showed that impact energy to the point of catastrophic failure (through-cracking) is related by a semi-empirical model to fiber properties, namely the strain energy to failure in tension of fiber/resin composite strands. On this basis, she suggested that "....the reinforcing fibers can be ordered in terms of energy absorbed in impact per unit composite weight from greatest to least: Kevlar 29, E-glass, Kevlar 49, and Thornel 300." Hybrids of Kevlar 49/graphite, which demonstrate an advantage over all-graphite reinforcement in total impact energy, have also been tested. An important conclusion of this work was that the relative impact damage tolerance of composites in certain situations can be predicted from fiber properties.

Based on Dorey's work, Evans and Masters [1987] found that whether delamination or flexure occurs depends on the relative values of the interlaminar shear strength, the flexural strength, and the span-to-depth ratio length to thickness. Based on these factors, impact damage is less likely when there are low-modulus layers on the outside of the laminate such as ±45 layers or Kevlar or glass fibers.

For many applications, moderate to high-modulus fibers of high strength seem to offer the greatest promise for improved impact resistance in low-velocity

impacts. The most effective use of impact-resistant fibers in composites has been when deployed in hybrid designs.

2.7.3 Hybrids

Hybrid composites are really a design invention whose purpose is to take further advantage of the flexibility of composites by combining composite components, usually different fibers or lamina, in ways to most effectively treat particular loading or environmental conditions with the lowest cost. The benefits of hybrid composites have been particularly noteworthy with respect to impact resistance.

As in other impact design techniques, the ability of the designer to take full advantage of hybrids is dependent on his or her ability to predict impact events, loading conditions in structures, structural effects on target response, and resultant failure modes. The properties of fibers and what they bring to the impact-resistant design, as discussed above, are applied in a real design sense with hybrids.

Renton [undtd] conveniently categorizes hybrids as follows: 1) interply (interspersed or core/shell), 2) intraply, 3) interply/intraply, and 4) superhybrids. The basic concept of the hybrid is that the additional material is selected to compensate for deficiencies in the base material, e.g., Kevlar or glass used to toughen a carbon/epoxy system [Marom 1986]. Others have done likewise for a variety of fibers (PE, PET, nylon, Kevlar, glass) [Jang 1989] and hybrid configurations [Jang 1989, Labor 1978].

Busgen, et al. [1989] demonstrated that a sandwich of Dyneema™ polyethylene outerlayers and carbon/epoxy as core material performed very well during impact. The compression-after-impact retention of this sandwich was about 80% up to incident impact energies of 12J, in contrast to 45% with a pure carbon composite. This

means a considerable improvement in the damage tolerance of structural composites. However, one must bear in mind the tradeoffs— the low melting point of polyethylene, low compressive strength, and high creep under constant load. Recently, Adams and Zimmerman [1986] demonstrated that a high-strength, high-modulus polyethylene fiber (Spectra 900) developed by Allied Corporation significantly enhanced impact properties when used in hybrids with carbon/epoxy.

Dorey [1978, 1984, undtd, 1987] has been a leader in investigating the use of hybrids to improve composites reliability in general and impact resistance in particular. In work with Sidey and Hutchings [Dorey 1978], it was shown that while Kevlar fiber-epoxy-reinforced composites had significantly better impact properties than carbon fiber-epoxy composites the static mechanical properties were half of the all-carbon-fiber counterpart. The hybrid systems they tested offered a good compromise between the superior in-plane, and flexural strength of the CFRP system and the impact properties of the KRP system. Analysis tools using laminated plate theory, like Tsai's microcomputer applications, can be used to optimize these in-plane properties for hybrids with respect to in-plane loads, while this work by Dorey and others gives insight into optimizing these lay-ups with respect to impact. The interaction of in-plane and impact loads is less clear.

2.7.4 Through-the-Thickness Reinforcements

2.7.4.1 Overview

Through-the-thickness reinforcements, such as 3-D braided and woven fabrics and stitching, have been shown to improve impact resistance. As crack stoppers and delamination arresters, these reinforcements confound cracks and delaminations by

physically preventing their easy propagation from an energy point of view. In the case of stitching, for instance, intraply microcracks would not be prevented from forming under an impact load, but the resulting delamination at higher load would be stopped and diverted in the presence of this through-the-thickness stitch, thus, either containing the damage or requiring additional energy to propagate it.

Taske and Majidi [1988a], using commingled graphite/PEEK, demonstrated that 3-D through-the-thickness yarns offer improvement in through-the-thickness impact properties. They reported that crack propagation resistance and energy absorption of these composites is related to the size and distribution of the resin-rich regions. These tend to act as crack arresters and energy absorbers. Additional energy-absorbing mechanisms, such as fiber bridging, fiber pullout, fiber breakage, crack deflection, and crack rotation may be involved to a much greater degree than in laminated composites of unidirectional laminae.

A number of through-the-thickness reinforcing techniques may be employed to improve impact resistance. Their effectiveness in coupon level tests can be measured by methods discussed previously as a function of strain energy release rate (G_{Ic} and/or G_{IIc})[1], compression or tension after impact testing, ultrasonic C-scan damage zone, and instrumented drop weight test data. None of the above can be easily related to design allowables for real structures.

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[1] As noted for CAI tests, G_{Ic} and G_{IIc} measurements may have questionable interpretations within the context of the assumptions of linear elastic fracture mechanics theory from which they derive due to the complicated nature of the damage modes and energy balance at play in these systems.

These techniques have shown great promise for improving the structural properties of composites and, in some cases, providing more cost-effective manufacturing methods. The improvements to impact properties generally come at some cost to in-plane properties. Other tradeoffs may include increased design (modeling and analysis complexity), processing, and manufacturing costs.

2.7.4.2 Braided Preforms and Woven Fabrics

The through-the-thickness reinforcement of woven or braided composites and resultant improvements in G1c G11c values has been investigated in terms of effects on damage tolerance and impact properties [Taske 1988b, Gong 1989, Gause 1987, Fang 1988, Chu 1987, Ko 1986a, Ko 1986b, Cantwell 1983].

Gong and Sankar [1989] performed sub-perforation impact tests of 3-D braided carbon/epoxy composites. The types of damage discovered were matrix cracking in resin pockets, matrix-fiber tow debonding, and fiber tow breakage in fiber bundle crimp areas.

Some workers have shown that braided composites exhibit better residual compressive properties than their corresponding angle-plied laminates by greatly limiting the extent of impact damage, and yet, exhibit similar strength and elastic properties [Gause 1987, Fang 1988]. In Fang's work the delaminated areas after impact were measured by using ultrasonic B-scan, C-scan and photomicrograph, and the damage areas were then correlated with the strain energy release rates GIc.

Variation on this theme include the work by Verpost, et al., [1989] in "2.5-D" reinforcements. They studied a unique approach to improving the G_{Ic} and G_{IIc} values (delamination resistance) of composite laminates using a 2.5-D reinforcement

reminiscent of Velcro®. Recognizing that composite structures are often rather thin plates, impact loads perpendicular to the plate can cause out-of-plane deformation resulting in bending and compression failure. Problem areas exist where out-of-plane stresses can build up: 1) bolted joints, and 2) adhesive joints and other discontinuities like laminate edges or internal ply terminations.

They found that the 2.5-D interweaving pile increases interlaminar delamination resistance by the following energy-absorbing failure mechanisms: 1) fiber breakage, 2) fiber pullout, and 3) crack deflection. An optimum pile density was determined for the materials tested based on G_{Ic}, fracture toughness.

2.7.4.3 Stitching

Stitching is simply the process of selectively introducing through-the-thickness reinforcement to areas in a structure where they are deemed vulnerable to out-of-plane loads, including impact loads, to improve the out-of-plane properties. Determining where stitching is appropriate is the function of a good impact design methodology as discussed previously. Besides the issue of where stitching is appropriate are the questions of the best "thread" material, stitch pattern, and stitch density. Bohon and Davis [1989] cite advanced textile preforms—woven and dry stitch—as advanced composites emerging technologies which are promising for improvements in impact resistance.

Ogo and Wilkins [1987] demonstrated that stitching of carbon/epoxy composite laminates resulted in significant improvements in out-of-plane properties (improvements in Mode I and Mode II fracture toughness with minimal degradation in in-plane tensile and compressive properties).

Methods of evaluating the effectiveness of stitching include CAI data, G_{Ic} and G_{IIc} fracture toughness, and ultrasonic C-scans for damage area assessment. The implications of data obtained from these tests to design are fairly clear. They are helpful in material screening, technique evaluation, and quality control; however, design allowables for real structures cannot be gleaned from these tests.

Correlation of data from tests involving questionable assumptions with respect to these systems, such as G_{Ic} and G_{IIc} strain energy release rates with C-scan damage area, should be interpreted with caution. Tradeoffs with in-plane properties will, in most cases, eventuate as a result of the use of through-the-thickness reinforcement techniques and, in some cases, material costs. Processing and manufacturing costs may also be greater.

2.7.5 Effects of Stacking Sequence and Ply Orientation

Thus far, the author has discussed the influence of modified constituents and some through-the-thickness reinforcement techniques on improving low-velocity impact resistance. While these offer intriguing and useful solutions for some applications, they will not work for others. In these cases, optimizing the stacking sequence of a laminate and/or the ply orientations may provide the required damage tolerance or durability. As can be expected, some design tradeoffs may result, such as increased part fabrication costs due to more labor-intensive lay-up schemes or changes to in-plane properties.

It has been shown unequivocally that both stacking sequence and ply orientation have significants effects on the impact resistance of a composite as it is measured by extent of delamination, energy absorption in instrumented impact testing, and/or residual strength measurements. For out-of-plane impact loads (as for in-plane

loads), Masters [1987a] notes that the types and modes of failure that are encountered depend upon both the direction of applied load and the orientation of the fibers making up the composite laminate.

The effects of stacking sequence and ply orientation on a variety of composite systems using experimental methods are well studied [Husman 1975, Chamis 1972, Chun 1986, Russell 1982, Stellbrink 1982].

Increasing ply thickness has been found to decrease the impact resistance of a composite as a function of delamination area. This can be seen in terms of a free edge effect given that intraply microcracks are analogous to a free edge and, thus, act as a stress concentrator [Wilkins 1983, Pagano 1973]. The effect of stacking like angle plies is to create thick plies, which contribute to poor impact resistance. Thick layers possess low tolerance to transverse strain generated during impact. The solution, while more manufacturing intensive, is to disperse plies of like orientation in a laminate. Rogers [1989a] suggests that no more than two plies of any orientation be stacked together. Furthermore, because ±45° laminates offer damage containment (high degree of damage tolerance), he recommends taking full advantage of this fact, particularly where shear loads are high, e.g., wing and rotor blade surfaces, by using these laminates. In any case, 0° plies should not exceed 60% of the angle plies and should be interspersed for the reasons given above.

Orientation of the lamination planes with respect to the impact load (perpendicular or parallel) is important and determines the failure mode as well as the amount of absorbed impact energy. Cross-ply laminates, although weaker than unidirectional laminates, provide the same impact energy absorption in flexure, since the dominant failure mode is delamination between layers [Broutman 1975].

Greszcyuk [Zukas 1982] reported that the influence of the fiber orientation-impact-induced damage zone is minimized if the layers are dispersed through the thickness and the fibers are placed in a bidirectional lay-up. A model which can predict delamination zones, ply by ply, in a laminate has been developed and experimentally verified by Gosse [1989]. It offers the promise of a predictive tool the designer may be able to use to assess the damage tolerance of composite structures of varying ply orientations and stacking sequences.

About the effects of stacking sequence and orientation on impact resistance Greszcyuk [Zukas 1982] concluded:

1) Bidirectional lay-up is more efficient in resisting damage than tridirectional or unidirectional lay-up.

2) Construction using complete dispersion of layers (having different fiber orientations) through the thickness is more resistant to damage than that in which the layers were not dispersed.

Dorey [1984] demonstrated that by putting the lower modulus 45° layers on the outside of the laminate impact resistance can be improved by protecting the load-carrying 0° plies and by reducing the flexural modulus, thus, increasing the strain energy capacity. Tradeoffs with respect to stiffness are obvious.

While most of the work on impact resistance has focused on characterizing, predicting, and modeling damage in thin orthotropic plates with idealized boundary conditions, a growing emphasis is being placed on understanding the role of structural configuration and constraint in the target response. Aspects of this issue are reflected in

the final three conclusions by Greszcyuk above, and are the springboard for the final section of this topic of methods and techniques to improve impact resistance.

2.7.6 Structural Configuration and Constraints

Structure clearly plays an important role in the impact resistance of a composite part. However, in most impact analyses the role of structural configurations and constraints cannot be satisfactorily considered because of its intrinsic variability and complexity. In real structures bending, local compression, affects of secondary structures, and damping are all mechanisms which contribute to the energy-absorbing capability of the structure. The location of an impact event relative to structural stiffeners, for example, has been shown to greatly influence the local impact response (thus, damage states and residual strengths) of the composite structures. Certainly, other structural artifacts, such as ply drops, joints, free edges, holes, etc., can all act as stress concentrators affecting the impact response of the structure. In Chapter 6 the effects of changing the annulus size of the specimen support fixture, on the damage modes and resultant damage state, are shown and discussed.

To underscore this, Dorey [1984] in investigating structural effects, showed that at relatively low velocity, where bending can occur in the laminates, no damage results if the energy of impact can be accommodated by the elastic strain energy of the laminate. A critical condition exists when local stress exceeds local strength. An important conclusion is that larger spans and thinner laminates cause flexure failure. More generally, the extent to which any one damage mechanism predominates depends on the materials properties, on the geometry or structural form, and on the loading conditions. This highlights the importance of the coupon test apparatus, particularly the choice of specimen test support fixtures, on the impact test results.

Dorey's work was corroborated by Evans and Masters [1987] when they demonstrated that whether a delamination or flexure failure mode occurs depends on the relative values of the interlaminar shear strength and the flexural strength and the span-to-depth ratio of the laminate.

Target curvature influences both the magnitude and distribution of surface pressure caused by the impact as well as the shape of the area of contact: (1) area of contact is elliptical and approaches a circle as the radius of the cylinder increases, (2) area of contact decreases with decreasing cylinder radius, (3) maximum load, resulting from impact, decreases with decreasing cylinder radius, (4) maximum surface pressure increases with decreasing cylinder radius, and (5) contact duration increases with decreasing cylinder radius [Zukas 1982]. These effects will, in turn, influence the mode and extent of failure. Cylinder boundary conditions will also influence the impact parameters and failure modes.

Enhanced stiffener design, reduction of part count, use of adhesive bonding, and improved joint design have a positive effect on the impact properties of composite structures [Bohon 1989]. The location of impacts with respect to stiffeners (clearly, a probability issue) also influences impact damage [Dorey 1987, Demuts 1985]. Tests by Demuts, et al. [1985] demonstrated that for multispar wing design of carbon/epoxy systems the higher level of complexity of the multispar design resulted in multiple load paths and generally a lesser degree of damage for a given impact energy, compared with simple coupon specimens without substructural members. More to the point, perhaps, is that the test coupon "substructural members" are very stiff test fixtures which contribute little to the energy absorption or dissipation mechanisms. This effect is

clearly seen in Chapter 4 in the finite element analysis of the impact test fixture. This may imply that designs based on coupon data may be conservative.

Furthermore, it has been shown that impacts near stiffeners may result in an altered local response so that damage is observed to one side or another of the point of impact. This effect of location of impact damage with respect to substructures was also discussed by Demuts [1989]. He noted that, "The critical location of an impact damage in the plane normal to the direction of travel of the impactor depends on substructural details such as spar, rib other stiffener spacing, and other structural details." Ramkumar [1983] has also identified substructural support stiffness and impact location as factors affecting low-velocity impact damage. For a 1/4-inch-thick laminate (approx 48 plies) impacted by a 1/2 inch blunt impactor, the internal damage (C-scan) decreased with distance from the spar or stiffener. Under 40 ft-lbs of impact energy, damage was greatest at the edge of a spar, less at the midbay with 4 inch spacing between spars, and still less at the midbay with 8 inch spacing. The least amount of delamination damage for all impact energies was found when impact occurred on the spar itself (where a local crushing effect is predominant). Other variables, such as impactor tip diameter, preload and panel thickness will also influence the damage modes and states.

In another study, Ramkumar [1981] considered the effects of impact on four locations of the F-18 wing section: (a) midway between the spars, away from the bay ends; (b) nearer, but not on the spar support; (c) at the corner where the spar and the rib intersect, but not on either support; and (d) directly over the support, between fasteners. The impact response was dominated by flexure for location (a), especially in the thinner laminate. When the impact location changes from (a) to (b) to (c), support constraints affect the response considerably. Finally, for impacts over the support (d), a local

crushing effect (indentation) is predominant. These results clearly demonstrate the crucial role structure plays in determining the target response and damage states.

The development of substructures for enhanced impact resistance is an important area of research. Coupling these enhanced designs with impact-resistant laminate stacking sequences, ply orientations, etc., in the early stages of design while simultaneously designing for manufacturing and the laundry list of "ilities" is the future of composites design [Loewy 1982].

2.7.7 Summary of Methods and Techniques for Improving Impact Resistance in Composites

The preceding discussion about impact represents only the surface in a sea of information, data and research in this interesting and vitally important area of composites research and technology. Because of the complexity of the problem it seems obvious that the opportunities for discovery and advancement of knowledge in this area are as exciting today as they were when the problem first surfaced in those early carbon/epoxy systems.

At the microstructural level the study of properties and behavior at the fiber/matrix interface and how they are affected by processing is an important research topic which will have profound influence on the ability to predict failure mechanisms and energy absorption mechanisms in impacted composite structures.

The development of tougher fibers and matrices and their role in enhancing impact resistance has been highlighted. And, the importance of manufacturing processes on the constituents in controlling the micromechanical behavior and, thus, the impact properties of the composite has been noted. The ability of the process to change

the chemistry and structure of the constituents (particularly at the fiber/matrix interface) as well as the introduction of defects in processing, such as voids, microcracks and the like can all contribute to the vulnerability of the composite structure to impact.

At the lamina level much research and development is being done to develop lamina properties which enhance the impact resistance of composite structures, including the use of fiber hybrids, optimization of matrix volume fraction, and the use of softening or buffer strips, interleafed prepregs, and localized adhesive strips.

In many cases, the choice of prepreg, with which the designer can work, is limited by practical considerations—cost, availability, stiffness or strength requirements, customer bias, lack of supporting test data for new materials, immature manufacturing methods, etc. In these cases, while the design or selection of a material system may be less than optimum from the viewpoint of impact resistance, the designer has available techniques which enhance the impact resistance of the laminate. These include using hybrids of different laminae, optimizing the stacking sequence, ply orientation, and selective use of interleafing at vulnerable ply interfaces.

At the laminate level, laminate analysis and design optimization software such as Tsai's GENLAM, LAMRANK and MIC MAC spreadsheets [Tsai 1988], or the University of Delaware's Composite Materials Analysis of Plates (CMAP) [Gillespie 1987] will provide effective laminate properties and strength predictions based on various failure criteria, quadratic in the case of the former and Tsai-Wu, and Maximum Stress in the case of the latter. They are based on classical laminate thin-plate theory, which assumes plane-stress and zero transverse shear deformation. Therefore, optimized laminates, such as those provided by LAMRANK, must be considered in the

context of impact, and changes made in stacking sequence and ply orientation based on currently available empirical and modeling data.

At the macrostructural, substructural, and component levels the role structure plays, in terms of the resultant damage area and post-impact properties, is critical, as noted by Demuts [1989]: "Among the various damage types examined, low-velocity impact is the most severe in terms of the damage areas and post impact mechanical properties. The critical impact damage location in a structure depends on the structural configuration and substructural member arrangement."

The development of through-the-thickness reinforcements such as stitching, 2-D woven fabrics, 3-D weaves, and braided composites have all been shown to improve impact properties under certain conditions; however, design tradeoffs can be expected. Likewise, stiffener placement and design, integrally molded stiffeners, and the reduction of stress concentrators such as free edges, holes, bolted joints, etc., have been experimentally demonstrated to influence the impact properties of composite structures.

Clearly, all of the above factors may affect the response of a structure to an impact load to a greater or lesser degree. Since that response certainly affects if and where failure will occur, the resultant damage state, and the residual strength of the structure, each of these factors should be considered in an impact-resistant design methodology.

2.8 Impact Design Heuristics

A list of heuristics categorized by structural level can be developed to aid the designer with first order impact-design decision-making information. The idea of such an expert knowledge assistant is to save the designer time and money in the early design stages by allowing him/her to quickly cull through the possible impact-design solutions. In many cases, heuristics are all that is available, given a lack of theoretical understanding of the physics of impact events and/or the computational gymnastics to reasonably predict material response under impact loads is not necessary or worth the time and effort ($). In Chapter 3 the author will show where and when in the design process these heuristics may be used for greatest effect. Impact design heuristics based on the following structural hierarchy are presented in Appendix A:

1) Resins

2) Fibers

3) Lamina

4) Laminates

5) Special Reinforcements

6) Design Features

7) Structural Configuration and Constraints

2.9 Summary and Challenges

In underscoring the challenge to composites, McDermott, in a recent article in *Advanced Composites 1990 Bluebook*, advanced an 18-point agenda "...gleaned from the comments of industry leaders over the past 18 months." First on the list of technical challenges for composites in the 1990's was "impact resistance and the combination of properties known as toughness."

The numerous variables involved in an impact event—structural, environmental, operational, impactor, material, and processing—suggest that some method which allows one to consider the critical variables and develop some predictions on their influence would be desirable. This presupposes the capability of some analytical, numerical and/or experimental method which allows one tc treat real structures with realistic loading conditions, and then make sense of the predictions from a design point of view. This is one of the remaining major challenges for solving the impact design problem.

Few adequate impact design tools exist to help the designer accomplish this daunting task; those needed include:

1) A coherent and comprehensive impact design methodology for composite structures built on a common design framework and including impact-specific design tools, analytical and heuristic.

2) Improved understanding of impact failure mechanisms.

3) Concurrent integration of impact resistant techniques with composite structure optimization tools.

4) Standard impact test methods which predict the effects of structure on impact.

5) Testing and analytical tools for predicting the effects of structure on impact damage and its effect on residual properties which take full advantage of CAE tools.

6) Standardize NDE and NDT method for impact testing, damage assessment, and damage detection.

7) An expert system for composites design and manufacturing which includes impact-resistant design incorporating 1) through 5) above.

Most of the methods discussed in the preceding sections target the improvement of one or more material parameters with respect to micromechanical, laminate, or structural properties under simple boundary conditions and with simple, usually no-load or monotonic loads.

It is the difficult job of the design engineer to sort through these with an appropriate design methodology which focuses on the voice of the customer, considers those critical to impact resistance simultaneously with other design requirements, and develop design concepts which best meet these requirements. Perhaps, the most useful general approach is the Total Quality Design framework and its accompanying tools [Henshaw 1989, Wilkins 1989].

With this methodology as a framework, a specific impact-design methodology has been developed and presented in Chapter 3. This Impact Design Methodology, as the reader will note, allows the designer to consider the what, when, where and how of designing for impact concurrently and in the context of other design constraints.

CHAPTER 3

A DESIGN METHODOLOGY FOR IMPACT RESISTANCE OF COMPOSITE STRUCTURES

Anything that one man can imagine other men can make real.

Jules Verne

3.1 Impact Resistance in Composites—A Concurrent Engineering Challenge

As noted in Chapter 2, it seems reasonable and necessary to treat impact resistance as a design problem within the context of other design constraints. It also seems prudent to think in terms of how one may achieve the best impact performance given other very real and, often, equally important design constraints, such as stiffness, strength, and cost. Perhaps this is done most efficaciously using a concurrent rather than the traditional (linear) approach to design. The capabilities, limitations, and misconceptions of the traditional approach are well noted by Henshaw [1989].

By using the so-called Total Quality Design (TQD) framework (a concurrent design approach) and philosophy, in conjunction with a variety of complementary design tools, impact resistance is treated in the global context of real structures concurrent with other critical design requirements. This framework and its role in the product development process provide the discipline to the creative elements of design, in general, and to impact design challenges, in particular.

Table 3.1 shows these initial phases of the product development process broken down into "create" and "evaluate" elements.

Table 3.1 Product Development Process Functions

Categories	Create (Brainstorming)	Evaluate (Discipline)	Design tools:
Team Building	1	2	TQD
Project Planning	3	4	MacProject II
Mission Statement	5	6	TQD
Customer List	7	8	Section 3.4
Customer Wants	9	10	Section 3.4
Competition	11	12	Benchmarking
Metrics	13	14	TQD / IDM
Concepts	15	16	TQD / IDM
Go/No-go Review	17	18	TQD / IDM

Attached to the framework of the methodology are impact design methods or tools which the designer uses for decision-making, analysis, and evaluation. Just as with the attachment of ligaments and tendons to the skeleton, the "where" of attachment of the impact design tools (and other "design for" modules) is critical to the effective functioning of the framework. These tools are either bundled in the Impact Design Module (IDM) and invoked as needed, or are more generally applicable design tools

which can be modified to handle impact design problems. An example of the tools which have been developed is an impact test program which uses finite element modeling and empirical data from a variety of test methods, including instrumented drop weight impact tests, to provide designers with a predictive tool for impact design in the case of low-velocity impact threats. Other tools include heuristics for selecting fibers, resins, stacking sequences, and ply orientations; materials databases; and simple structural analysis software.

The thrust of this approach is to use tools, such as finite element analysis, interactively and simultaneously with testing to reach the best design solution, rather than simply as a method of checking a design, as is the traditional FEA approach. The interaction of variables in a structural analysis should be treated as realistically as possible. Through the use of an interactive and iterative process of design, analysis, and testing, along with a coherent test design strategy, maximum effective use of resources can be achieved and an optimum design realized.

3.2 Why an Impact Design Methodology?

The complexity of the impact event and the associated failure modes in composite structures demand this coherent and comprehensive design methodology by which impact resistance can be systematically designed into composite structures. However, this does not mean to imply yet another stand-alone "design for" process or method layered on top of the already myriad such approaches for everything from "design for cost" to "design for manufacturing." As mentioned above, to be effective and realistic this design methodology must address impact resistance as one of many "design for" considerations. An appropriate design methodology accounts for this by

addressing design tradeoffs in a concurrent, comprehensive, and disciplined manner. At best it is part philosophy and part prescriptive recipe intertwined, so as to make one part dependent on the other, always leading the designer to the "best" of all possible design solutions in an "uncertain and changing situation" [Koen 1985].

In this chapter, we describe the Impact Design Methodology, its elements and how it would be employed in a design problem where low-velocity impact damage is a threat. The Total Quality Design (TQD) methodology developed by Henshaw and Wilkins [1990] provides the framework for the Impact Design Methodology. Two of its important tools, the House of Quality and Pugh concept selection process (described in Chapter 2), are highlighted. Important aspects of the methodology are where and when impact design criteria are considered in the design, as is the integration of testing and analysis of structures and materials which assist in the design-decision process.

However, before describing the methodology it is important to briefly consider who might benefit from such a methodology, i.e., who are the customers and what are their wants.

3.2.1 Who are the Customers?

In the process of brainstorming a list of customers for an impact design methodology, we found it to include designers, engineers, university researchers, program managers, and laboratory technicians as well as composite materials suppliers, designers of impact test equipment, and end-product users. In short, persons from academia, government, and industry who could benefit directly or indirectly from an improved impact design approach would be customers of this methodology. The critical few customers of an impact design methodology are listed in Table 3.2. (A complete list

of customers, identified by name where possible, is provided in the TQD Excel spreadsheets used for evaluating the methodology.) The customers are compelled, by a variety of motivations, to improve the durability and damage tolerance of composites.

Table 3.2 Impact Design Methodology Customers

Customers	Relative Importance
1) CCM Consortium Members	5
2) CCM U.S. Government Sponsors	5
3) End-User (OEM)	5
4) CCM Staff and Faculty	4
5) CCM Students	3
6) Others involved in impact design and testing	3

3.2.2 What are the Customers' Wants?

The wants or needs of these customers (also addressed to some degree in Chapter 2) include an impact design methodology which is coherent, comprehensive, simple, inexpensive to employ, integrated with other design for methods; and results in the best or optimized impact design solutions. It must also be fast and flexible, and should eliminate unproductive design, testing, and analysis. These wants were generated through an extensive literature search, discussions with members of the CCM industrial consortium, CCM staff, faculty, and students. They were evaluated using the

House of Quality technique and used in developing and comparing our methodology with other methodologies by means of the Pugh concept selection process. The most important customer wants are shown below in Table 3.3.

Table 3.3 Impact Design Methodology Customer Wants

Customer Wants	Relative Importance
1) Comprehensive and coherent methodology	5
2) Use impact test data in design	5
3) Impact design criteria	5
4) Standardized/flexible test method	4
5) Easy to use CAD/CAE tools	4
6) Understand apparatus influence on response	4
7) Inexpensive test method	4
8) Impact design heuristics	3
9) Impact resistant techniques	2
10) Impact resistant composite materials	2

3.3 Total Quality Design Framework—A Better Design Approach

The first step in any design process, after defining the objectives of the problem (mission statement) and selecting the team to work it, is to know the customers and their wants and to translate these wants into engineering metrics which we call quality metrics (QM's). Alternating "create" and "evaluate" activities produce the

necessary list of the "critical few" CW's and QM's, their correlations, and some measure against a standard or benchmark. It is during this first phase or step that the design team focuses on the key issues and challenges of the design, including issues relating to impact resistance. The steps of the Impact Design Methodology are presented in the following sections with explanations where deemed necessary. A flow chart of the entire process and TQD spreadsheets of the Impact Design Methodology are presented in Appendix B.

A caveat is in order here. Although the process flow chart suggests a rigid sequentiality to the design process, it not the author's intent that it should be viewed or used in this manner. In reality, during the early stages of design, the order or time spent on each of these elements is not as critical as one's awareness of the importance and interrelationships of each. That each should be identified and thoroughly addressed is important. The automated project planning templates allow the team the flexibility to plan and adjust the process as befits their particular circumstances, yet still "cover all of the bases."

3.3.1 Assessing the Opportunities and the House of Quality

Figure 3.1 shows this phase, the first step of which is to *Identify the Application*. Using the TQD framework as a starting point for the design process the application is identified and the problem(s) defined. This methodology is designed to be flexible in that it can be modified to fit the specific nature of the design project. It is equally capable of expediting the redesign of a maintenance access door for an existing helicopter or designing a "clean sheet" composite helicopter of the future. Only the complexity of the project, not the process, will change.

Design issues which are of critical importance and impact on the early success of concept development, evaluation, and design are those relating to team selection and team building. These have been thoroughly covered by Henshaw [1989] and, while not explicitly addressed here, must be considered very early in the project and monitored throughout the effort.

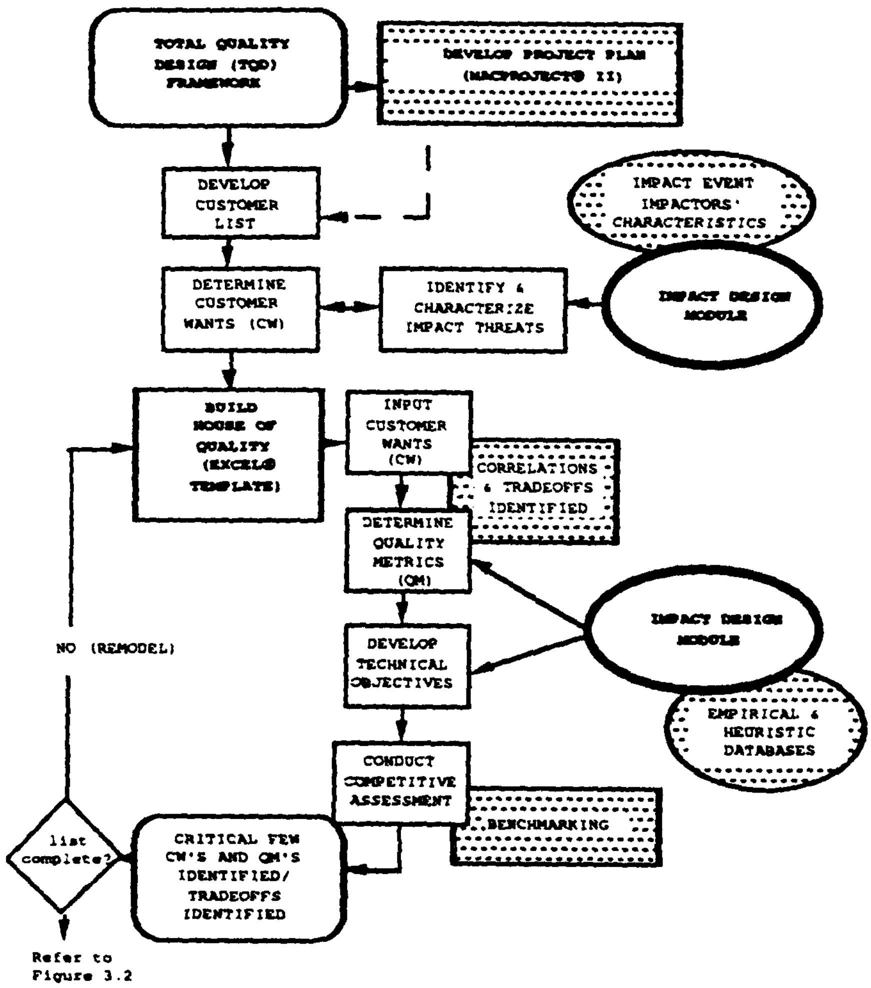

Figure 3.1 Assessing the Opportunity—House of Quality. Of significance to "design for" impact are when and where impact issues are considered.

3.3.1.1 A MacProject® II Template for Planning

Development of a project plan and planning documents should be performed at this phase or the project formulation phase which immediately precedes it. A project planning template, developed in MacProject II (PERT- and CPM-based) is included in Appendix C. It is designed to help the design team organize, schedule, resource, and track project status. It further provides the flexibility and computational ease to perform fast "What if?" drills. Familiarity with MacProject II is essential; however, this can be achieved in one or two hours, if one is versed in the fundamentals of project planning. Included with the planning template is a list of suggested outputs from each phase of the methodology, including those specifically addressing impact design issues.

3.3.1.2 Listening to the Voice of the Customer

A critical premise of the Total Quality Design framework [Henshaw 1989] developed from the Improved Product Development Process [Clausing 1986] and the House of Quality [Hauser 1988] is that the customer's voice be heard throughout the development process. The Impact Design Methodology employs this philosophy, as well. The initial steps are simple, yet critical to insuring that this is done. In the case of impact resistance, this not only means that one must understand what the customer means by a product that must be durable or damage tolerant, but also, how to translate these wants to meaningful quality metrics for design and then test or analyze for impact, against these metrics. The IDM and proposed impact test strategy address the approach one might take. But first, one must identify the customer.

The design team should list all the customers for the project. The use of Total Quality Management (TQM) philosophy and brainstorming techniques are effective

in the creative phase of this process [Wilkins 1989]. It is important to identify customers by name, whenever possible.

After evaluating and culling the customer list to those for which the design will focus, it is necessary to identify the customer wants (CW). This is not necessarily a simple task; however, there are a number of useful tools to help in the process. These include the following: literature survey, questionnaires, personal interviews, site visits, advertising literature, benchmarking of the competition, existing market research, and brainstorming. Henshaw [1989] suggests generating customer wants lists for each customer through the variety of techniques listed above and then evaluating them for correlations—positive and negative. Having a customer on the design team is also essential to this process [Henshaw 1989]. These wants can also be categorized and classified hierarchically for simpler evaluation. The author took this approach, categorizing each CW by customer, showing the correlation between specific CW's and particular customers.

The essence of this list is determining "what" the customer wants in a qualitative sense, rather than "how" these wants are to be achieved. The essence of design is translating the "whats" into the "hows".

3.3.1.3 Identifying and Characterizing the Impact Threat

At this point, the analysis should include the probability of occurrence of particular *impact threats*. Brainstorming and disciplined evaluation can be performed alternately to develop a reasonable list. This step is crucial to an effective design, since all the other impact design considerations and assumption as well as the test and analysis strategy, will be based on the expected impact threats.

Low-velocity impact events were of primary concern in our research. These are commonly classified as "tool drops", foreign object damage, manufacturing and handling damage, and the like. In the case of a large system—for example, a helicopter—impact threats will vary from location to location on the structure; therefore, it is essential that the entire structure be evaluated. Those areas which are deemed most vulnerable and/or have the highest sensitivity to damage, requiring a damage tolerant design, should be the major focus of the design team's efforts. The design should be optimized with respect to impact resistance in these areas of high vulnerability. Composites, in particular, allow the designer incredible flexibility in doing this. When changes are made to structures, materials, performance requirements, threat, etc., the impact-design decisions must be reconsidered.

If low-velocity impact is of concern, and other design constraints suggest that a composites solution will be effective, then the IDM can be invoked, as shown in Figure 3.1, with other composite module design tools to assist the design-decision process. The IDM will include knowledge cells of heuristics and empirical databases as well as analysis and theory which can be applied to the problem.

A feedback mechanism in the methodology allows updating of the IDM with information developed during the determination of the CW's. Ideally, this feedback mechanism would be automatic and unobtrusive as the IDM expert assistant learns from the efforts of the design team over a period of time involving many projects. It would purge incorrect information as new data becomes available, update existing data, and add data representing new knowledge.

3.3.1.4 Determining the Relative Importance of the CW's

After the CW's have been generated through the various creative methods described above, and the impact threats identified, a disciplined manner of evaluating of relative importance of these CW's must ensue. A simple scale, for example, "1 to 5" should be used to judge the CW's from greatest to least importance. This ranking is important because it focuses the product development team's efforts on the most important CW's. The bulk of the team's resources should be devoted to insuring those CW's with a high relative importance and strong correlation with associated Quality Metric's (QM) are satisfied [King 1987, Henshaw 1989]. This is not meant to imply that other CW's are ignored, only that they are treated in a more routine manner. In particular, where impact resistance is indicated as a strong CW, one may find it difficult to determine appropriate QM's. At this point, the IDM would be invoked to assist in making this correlation. QM's relating to impact resistance might include high fracture toughness of the matrix, high strain to failure of the fiber, high 90° strain-to-failure value, high G_{Ic} and G_{IIc} values, particular stacking sequences of the laminate, special stringer configurations, etc. The specific application and impact threats will determine which of these, or other QM's, are pertinent. It is reasonable to expect that early decisions for selecting material systems will focus on the constitutive and lamina properties, and the QM's pertaining to these. Tradeoffs between impact resistance, manufacturing, and in-plane properties, particularly stiffness, are likely to surface in a design demanding the advantages of high-performance composites.

3.3.1.5 Identifying Agreements and Conflicts Amongst CW's

An important part of the House of Quality process is to apply a discipline to the evaluation of the CW's developed in the creative phase of the process. This

evaluation requires that conflicts amongst those CW's with high relative importance be identified. For example, if both high in-plane stiffness and high impact resistance have a relative of importance of "5" (very high) the design team would be alerted that design tradeoffs with respect to materials, configuration, and/or manufacturing methods may need to be considered in the design. In an instance such as this, one of a variety of damage containment techniques or localized through-the-thickness reinforcements may be appropriate to locally improve impact resistance in the affected structural locations. A tradeoff between these competing criteria would be identified through acceptable analysis and testing. Suggestions as to appropriate techniques would ideally be available to the designer by invoking the IDM.

3.3.1.6 Building the House of Quality

As with other design for considerations, threat analysis for impact is developed through the evaluation of the CW's. These are carried through the HOQ and Pugh process along with the other CW's. The functions of the House of Quality are to ensure 1) each CW's relative importance is identified; 2) quality metrics (QM's) are determined, correlated and assigned technical objectives; and 3) QM's are correlated with CW's as well as with the benchmark [Henshaw 1989, King 1987, Hauser 1988].

From the preceding discussion, we can take the following steps toward building the House of Quality: (An Excel HOQ template has been developed for this purpose by the Center for Composite Materials)

1) *Input Customer Wants (CW)*, including impact threats.

2) *Determine Quality Metrics (QM).* These must be measurable

characteristics which relate to the design requirements (CW), for example, G_{11c} may be a quality metric for laminate impact resistance.

2) *Correlate CW's with QM's.* Where positive correlations exist, a synergistic effect results. Where negative correlations exist, design tradeoffs may be required. These correlations are particularly critical where they occur with CW's of high relative importance.

3) *Identify "critical few" CW's and QM's.*

4) *Correlate QM's.* This may also result in either synergy (positive correlation) or tradeoffs (negative correlation) of impact resistant QM's with other QM's.

5) *Determine technical objectives* for QM's and their difficulty of achievement. Technical objectives identify the design allowables for QM's. The difficulty of achievement rating suggests the technical difficulty of meeting these QM's. Those QM's with high correlation to important CW's and great technical difficulty will require special attention by the design team. Resource planning for the technical objectives of these QM's should be made accordingly.

6) *Conduct competitive assessment with the benchmark.* If the product to be designed is competing with an existing product, benchmarking should be accomplished to assess the competition's ability to meet the critical CW's and QM's identified in the House of Quality. Henshaw [1989] and King [1987] discuss these benchmarkii g .echniques. One

must look for opportunities to exploit weaknesses in the competition and for the strengths in the benchmark from which one's design can borrow.

At any point in the development of the House of Quality, the team may deem it necessary and prudent to invoke the IDM for insight into a variety of potential techniques at micro- or macro-structural levels, which could establish critical QM's and determine technical objectives.

The most important output of the House of Quality process is the identification of the critical few CW's and QM's for the design. In particular, those relating to impact resistance for which design solutions may not be evident. These design criteria represent the engineering translation of the CW's and are carried through to the next step in the process; the Pugh concept selection process. In this way, the voice of the customer continues to be heard, but now in a way that the designer can develop it into a concept, design, manufacturing process, etc.

3.3.2 The Pugh Concept Selection Process

The use of the Pugh concept selection process proved to be particularly useful in bringing a discipline to the process of evaluating a variety of impact resistant concepts for the critical CW's and QM's developed in the House of Quality. It is an iterative process which will converge to the best one or two design approaches.

As shown in Figures 3.2 and 3.3, the Pugh process may be quite involved, as in the general case of systems development; however, it can also manifest itself as a simple tool for treating a smaller design problem, such as the redesign of an aircraft belly skin. In either extreme, elements of creativity and analytical discipline are applied to the problem in a flexible and tailorable manner.

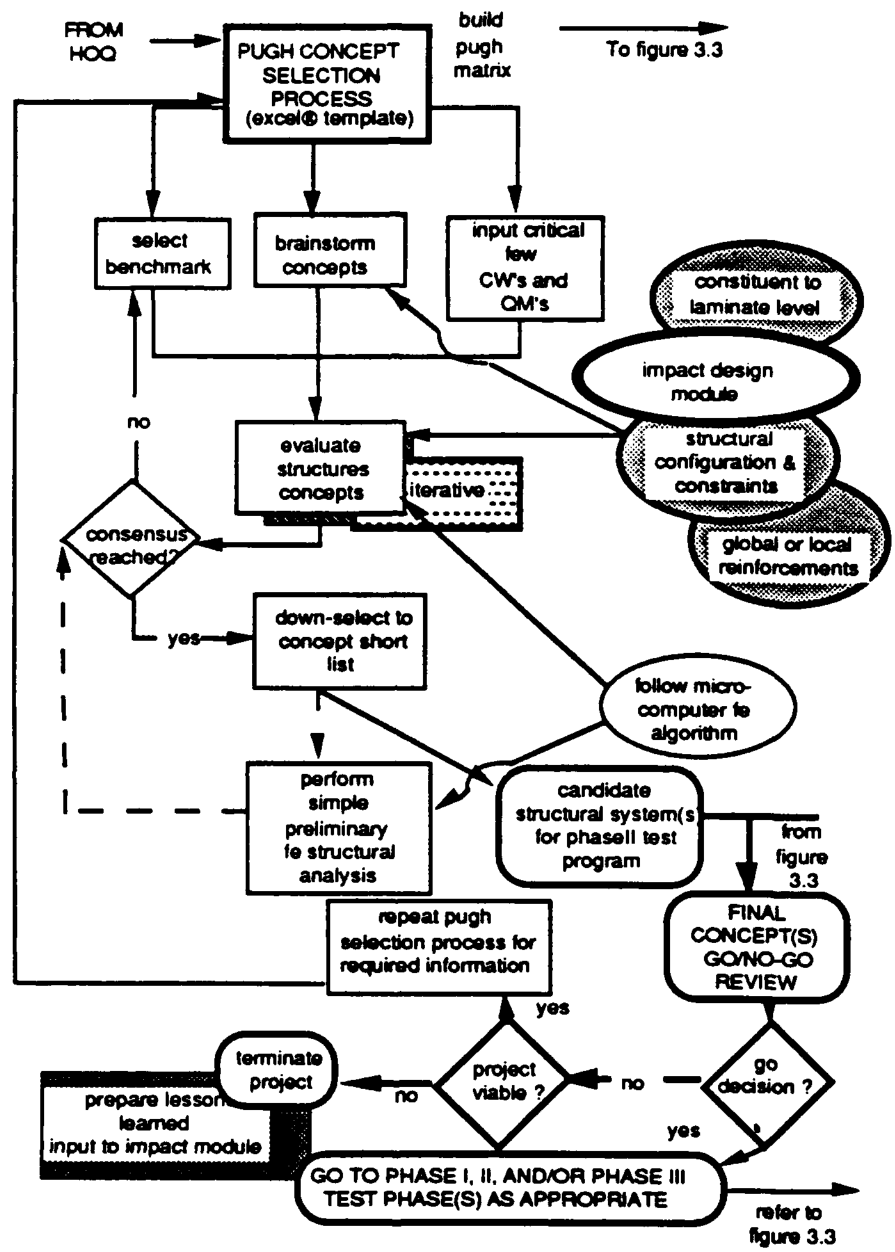

Figure 3.2 Pugh concept selection process for structural components and the interfaces with the IDM and finite element algorithms. Note the concurrent treatment of materials selection in Figure 3.3.

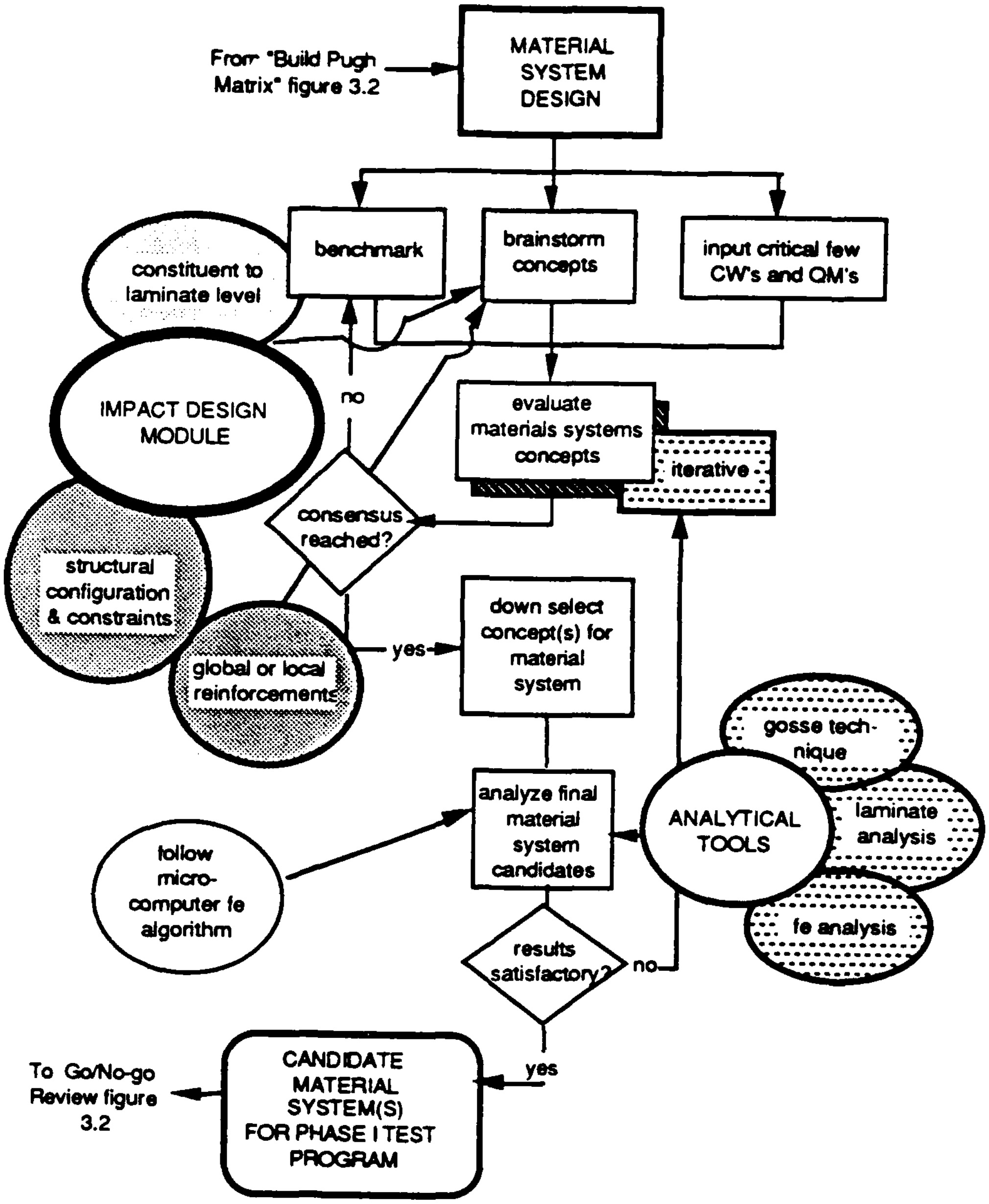

Figure 3.3 Pugh concept selection process for material systems. Note the interface with Figure 3.2.

Figure 3.2 also demonstrates at which point in the Pugh process impact issue would be considered, and analytical or numerical methods employed to evaluate structural and material systems concepts.

The Pugh process matrix is also available as an Excel template, developed by CCM, which facilitates its use. The steps in this process are briefly discussed in the following sections along with their connections to the IDM. Development of the structural concept and material systems will most likely (and effectively) be done concurrently. Nevertheless, each project will be unique in regards to the sequence and scope of treatment of each element in the process.

Of particular importance to the maintenance of the IDM, is a procedure for insuring feedback of lessons learned data throughout the process of design, testing and analysis during each project. An adequate feedback mechanism will perform a quality control function on the process.

3.3.2.1 Brainstorming Concepts

Brainstorming structural concepts, selecting the benchmark, and inputting the critical CW's and QM's will generally be conducted in parallel. The latter two activities will be outputs from the House of Quality and so may be accomplished quickly. On the other hand, developing concepts will require more time and effort. The Pugh matrix shell will be built and populated from this step onward.

With respect to impact issues, invoking the IDM—structural configuration and constraint—will assist the concept development process.

At this stage in the design, the design team will consider heuristics as they apply to part-count, stiffeners, stress concentrators, etc. Concepts development and evaluation will coincide with development of material systems concepts and preliminary investigation of manufacturing processes. Impact testing of materials and structures could be conducted concurrently with concept selection, given reasonable lag time for developing concepts. This would depend on a number of factors including resource availability, the type of development effort, and the project complexity. The project leader can easily perform "what if?" exercises in the management of project resources using automated project planning documents such as those discussed in Section 3.4.1.1.

3.3.2.2 Selecting the Benchmark

By this step, much of the benchmarking work has been done in the House of Quality phase. The benchmark values for selected QM's and CW's are evaluated for inclusion in the Pugh matrix. Since benchmarking is a dynamic process, it is likely that new information from the market research or preliminary analysis and testing will be available to update the benchmark datum line. It can be expected that little helpful information will be apparent about the impact resistance of the benchmark; therefore, the design team should anticipate a requirement to perform independent analyses and tests to identify these characteristics.

3.3.2.3 The "Critical Few" CW's and QM's from the HOQ

This step is self-explanatory; however, as in the case of the benchmark, the design team should be sensitive to new data which suggests changes in the CW's, QM's or their relative importance. From the literature, critical wants for impact resistance in structures will likely relate to such things as part count, stiffener design, and the

presence of stress concentrators. While those for material systems will focus on matrix toughness, fiber strain-to-failure, fiber/matrix interfacial adhesion, laminate stacking sequence, global or local reinforcements, etc.

3.3.2.4 Evaluating Structural Concepts

The information is now in place in the Pugh matrix to evaluate the structural concepts. Among the many design considerations, the design team would apply heuristics from the IDM and analytical models to evaluate competing concepts for impact resistance. The concurrent evaluation of material systems and structures is necessary for an optimum solution since these variables are dependent on one another; however, this is not necessarily a negative, since impact resistance synergy may result from certain combinations of materials and structures. On the other hand, the designer can expect to confront the need to perform tradeoff analyses with cost, performance, producibility, and other "ilities" in the search for an impact resistant design solution.

The use of simple finite element analyses for purposes of gaining insight into the structural behavior of the concepts as well as the benchmark, may be advisable at this point in the evaluation process. Other tools, such as Tsai's laminate analysis software [1988], provide quick and easy checks on proposed laminates in terms of materials, stacking sequence, and orientation; given in-plane loads and/or displacements. These tools, when used in conjunction with the IDM, will help to optimize concepts with respect to in-plane as well as out-of-plane properties.

Whether or not one conducts finite element structural analysis at this stage in the process will depend on 1) the number of candidates to evaluate, 2) the availability of other information and analytical tools to discriminate amongst the concepts, 3) the costs

involved in performing the analysis, and 4) the time available to make these early concept down-select decisions.

The Pugh process is repeated until consensus is reached on a best concept(s). Concepts may be redefined, combined with others, or otherwise modified to arrive at the best solution. The benchmark should also be changed as needed to refine and evaluate concepts. It is desirable to eliminate concepts using the minimum number of evaluation/analysis tools; for example, it would be desirable to eliminate a concept without the use of finite element analysis. It is reasonable to expect that analysis and perhaps testing procedures will be employed when one concept is not clearly superior to another based on the initial cursory comparison of QM's and CW's. Use of simple materials screening test data, such as that obtained from flexure, DCB, CNF, or ENF testing could be used to down-select materials with respect to interlaminar properties; an important impact consideration. Optimizing one's resources is critical at this stage. As noted by Henshaw [1989] and Hauser and Clausing [1988], the Pugh process must be used judiciously and numerical scores evaluated with care. The primary function of this step is rapid convergence to a concept(s) based on the "critical few" CW's and QM's.

After evaluating the concepts with the Pugh process, the team would down-select to a concept short list. This list would consist of one or, at most, two promising concepts to be developed and evaluated further.

3.3.2.5 Analyzing Final Concepts

If finite element analyses were not previously performed, the team would develop simple structural FE and analytical models for evaluating the final concepts at this stage in the Pugh process. (This would also be done for materials systems.) The

finite element algorithm presented in Chapter 4 suggests an approach for building these models and refining them to the level necessary to make a decision.

Crucial to this effort is the definition of loads and boundary conditions. The critical CW's and QM's can help to define these along with the emerging structural detail of competing concepts. Finite element heuristics and guidelines for building models are provided in Appendix D. Models should be checked for integrity and accuracy and refinements made only to a level necessary to understand structural behavior and discriminate between concepts. As before, it is recommended that the same level of FEA be conducted on the benchmark for purposes of comparison with these final concepts.

Common structures such as I-beam stiffeners, hat stiffeners, core materials, joints, etc., could be premodeled and maintained in a sub-module of the IDM. These template models could be invoked, and the geometries, material properties, loads and boundary conditions changed to reflect the particular case of interest.

Once the overall structural behavior of the concept is understood, one may refine the model with fully anisotropic material properties. This would be accomplished in the first part of Phase II testing. FE models from simple analyses would then be exported from MSC•PAL2 (on the Macintosh IIx platform) in Bulk Data File (BDF) format to MSC•NASTRAN, where the material properties would be changed to reflect the designer-selected composite material system. The analysis at this higher level of complexity would be performed on the DEC VAX or IBM 3090, and results exported to MSC•PAL 2 for post-processing.

These FEA models would be used to evaluate the global effect of candidate substructures which may be tested for impact resistance. The prediction of the global force-displacement response up to the 90° failure strain, $\varepsilon_{90°}$, is critical at this stage (see Figure 3.4), as this value represents the lower bound of performance in composite laminates as measured by damage initiation due to intralaminar matrix cracking under impact loads normal to the surface of the structure.

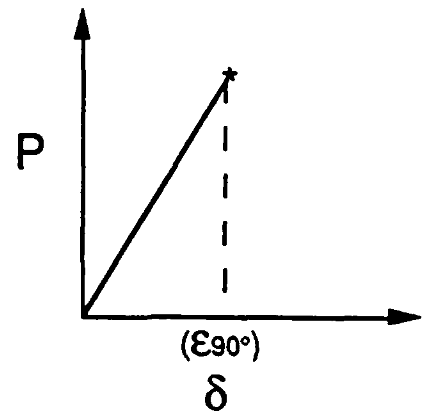

Figure 3.4 Global load-displacement response of a structure subjected to impact loading. Prediction of force-displacement response up $\varepsilon_{90°}$ is crucial.

While the constitutive properties are important in determining this value, the structure's response (compliance) to impact loading is equally important. This is the crux of the FE modeling and analysis; success in this step allows direct comparison with like material systems' responses in the test phase of the program. The designer's ability to predict global structural response in the candidate structures allows him/her to

effectively reduce the list of concepts prior to the test phase of the program and to do so in a scientific manner rather than a purely heuristic or empirical approach.

3.3.2.6 Candidate Structural System(s) for the Test Program

The primary output of the HOQ and Pugh concept selection phase of this methodology is represented by a well conceived, formulated and analyzed concept for both the structure and the material systems that compose it. Proper application of these tools should allow the design team to present supportable recommendations for continued product development at a Go/No-go review.

3.3.2.7 Material Systems Design

Generally, what has been said about structural concept selection applies equally to material systems. As shown in Figures 3.2 and 3.3, material system selection will typically be done concurrently with structural concept selection. The concurrent design of the structure and the material system is necessary to take full advantage of the properties of composite materials in general and impact resistance, in particular. In other words, a decision made on structural configuration will influence decisions on materials and vice versa. A similar argument can be made for other "design for" considerations, such as manufacturing.

Some aspects unique to material systems concept selection are presented below as a complement to the discussion of the Pugh process for structural concept selection.

Brainstorming concepts for material system(s) will be performed in the same way as for structures. The IDM will be of assistance in this process and includes

information about selection of fibers, resins, prepregs, stacking sequence, etc., to assist in the impact design decision-making process. Other "design for" modules will be invoked as needed for tradeoff analyses, such as cost, manufacturing, and repairability.

Benchmarking materials systems and designing for local impact events will follow the same process as with the structural benchmark. The critical few CW's and QM's from the HOQ will be inputted to the Pugh matrix, and material systems concepts will be evaluated. Iterations of the this process will be conducted as required to reach the best design solution within the available evaluation time.

After down-select concepts of the material systems concepts, candidates will be more rigorously evaluated using quasi-isotropic composite material properties for inclusion into the finite element model(s) of the most likely candidate systems for the preliminary evaluation of the system structural response. The results of this analysis will represent the lower bound of in-plane performance. These properties may be determined from analytical tools such as SMC (micromechanics), CMAP, GENLAM, LAMRANK (laminate analysis) and/or Mic-Mac's (structural analysis-plates, beams, shells, tubes). Understanding the loading conditions is very important as this directly influences the laminate design. With the LAMRANK software, the laminate ranking output for a given material system will depend on the loading conditions you assign. It is important to note that these laminate rankings will not be optimized with respect to impact loadings.

FEA may initially be performed on candidate systems using quasi-isotropic materials, with subsequent optimization of the laminates with respect to in-plane loads. These optimized laminates will then be evaluated for performance under impact loads

using available modeling and analysis techniques, such as those developed by Gosse [1989].

Where analysis indicates high vulnerability to impact events, global or local reinforcement (other than that provided by constituents) should be considered to provide the necessary impact resistance, durability, damage tolerance, and/or damage containment. The IDM will be helpful in selecting these impact resistant techniques for consideration in your design. They include the use of through-the-thickness reinforcements (stitching, weaves, braids), damage containment techniques (tear strips, softening strips, interleafs, etc.) for damage tolerant/sensitive areas. The influence of these techniques on toughness should be considered and tradeoffs identified.

The result of this process is a firm supportable list of candidate material system(s) for Phase 0—1 of the test program. (Some of the required testing may already have been conducted during this process or during previous studies. The results should be in the a materials property database in the IDM or some common composite materials database.)

It can be seen that these procedures borrow from the building-block approach to a damage tolerance design methodology discussed in Chapter 2; however, they differ in that the HOQ and Pugh process have been used, along with a variety of design tools, in the context of Sjoblom's global view of impact, to select important test variables and to systematically reduce the number of materials and structures which might be considered for impact resistance.

3.3.3 Final Concept(s) Go/No-Go Review

A "Go" decision most likely results in the commencement of the test phase of the methodology. Where one begins within the test phase will depend on a number of factors which have already been mentioned. A "No-go" decision will result in one of two decisions: 1) termination of the project, or 2) return to the Pugh selection process. A decision to terminate could be based on a variety of factors, financial, technical, etc., whereas, a decision to revisit the Pugh process is probably based on some identified risk(s) requiring additional study. In either case, valuable information has probably been gained which should be included in the IDM for the benefit of future projects.

3.4 Test Design for Impact Resistance

The role of testing within the Impact Design Methodology is crucial to the impact design process. It is clear that analysis and computational methods alone cannot provide answers to the problem of predicting the response of a system to low-velocity impact. Therefore, it is reasonable, indeed necessary, to use empirical techniques to fill in these knowledge gaps for the real materials and structures with which we are concerned.

It is also obvious that testing adds to the cost—in terms of time, money, and personnel resources—of the product development. Therefore, the test strategy employed by the designer must focus on solving the problems identified by the application. The goal is to have a strategy which results in the absolute minimum testing required to select the best concept. To accomplish this, the test plan should be designed to interactively support design and analysis activities.

The methodology proposed here does that by introducing test design, and planning at the most effective point in the design process. The critical response and control variables for the design are identified during the House of Quality phase. And, in the case where the relationship between these variables is in question, they may be understood more clearly with a well conceived test program. The role of test and experiment design will be more fully discussed in Chapter 5.

The following three sections discuss phases of testing which directly support the Impact Design Methodology. When and to what degree these will be applied depends on the particular design problem. For example, it is reasonable to consider coupon testing for evaluating design allowables for material systems' QM's as early as the House of Quality phase, if accurate or reliable test data or theoretical bases do not exist to clearly establish valid technical objectives for these QM's.

3.4.1 Phase 0 and I—Coupon Tests

Testing plays an important role in the design of impact resistant structures. In the absence of standardized impact test methods, an ad hoc approach has been taken by designers to assess composite materials and structures for damage tolerance and durability. Laboratory test methods, such as compression-after-impact testing, have been used principally for material screening and quality control; however, values reported for these tests have little meaning from a design sense.

In this methodology, testing takes its place alongside analysis and design as a critical information source for the designer. An appropriate test design strategy is deemed essential to assuring minimum testing costs and maximum impact design information. For this reason a simple trial and error strategy is rejected as too

inefficient. The details of the test strategy and experimental design used in this study are discussed in Chapter 5.

The purpose of impact testing is to verify analytical and/or numerical predictions of materials and structural response with the goal of selecting the most promising material system and structure, with respect to impact resistance. A modified building-block test methodology is used in conjunction with design and analytical activities during the House of Quality and Pugh concept selection phase of the design process. The first test phase—Phase 0 and 1 Coupon testing—has two primary goals: 1) develop data for establishing technical objectives for Quality Metrics (QM's) in the House of Quality design phase (Phase 0), and 2) screen candidate material systems developed through the Pugh concept selection process (Phase 1). See Figure 3.5.

3.4.1.1 Identifying the Response and Control Variables

The first step in this phase of testing is to determine the control and response variables of interest. The House of Quality, generally, will provide the response variables as quality metrics. Identifying the control variables—of the myriad possible—which will have the strongest influence on the response is a difficult job; however, information and insight can be gained from the IDM, Phase 0 testing, and/or additional literature survey. Design constraints may necessarily preclude certain material or structural options which might otherwise be desirable to consider as dependent control variables, for example, cost constraints may preclude consideration of certain high performance thermoplastics, otherwise desirable from an impact point of view. Again, these constraints and tradeoffs will be identified through the House of Quality.

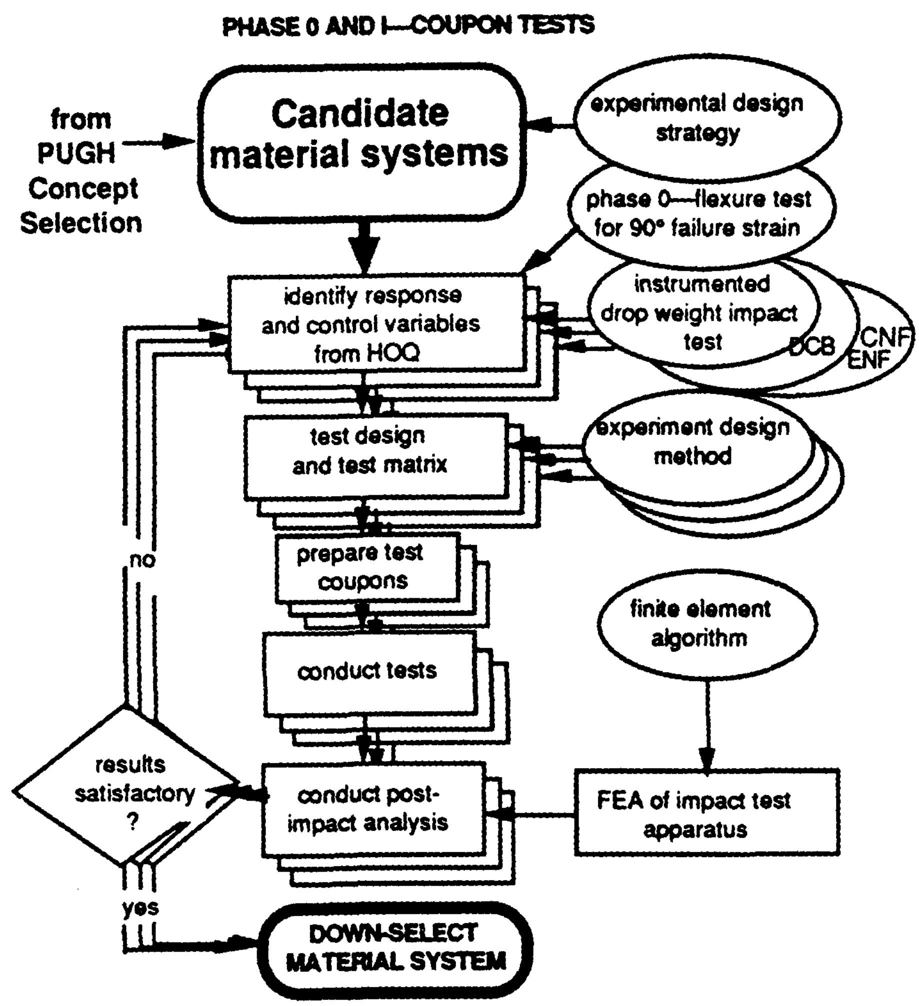

Figure 3.5 Phase 0 and I—Coupon Tests flow chart.

Examples of tests which may be considered at this phase in the testing are Double Cantilever Beam (DCB) and End Notched Flexure (ENF) for prepreg toughness—response variables G_{Ic} and G_{IIc}, Izod or Charpy testing of neat resin for fracture toughness—response variable K_{Ic}, Center Notched Flexure (CNF) for dynamic fracture initiation and propagation energies, instrumented drop weight impact

test results—response variables damage zone, initiation energy to damage, propagation energy, compression-after-impact strength or other response variables deemed pertinent, and modified three-point bend flexure testing in point-loaded specimens for 90° strain-to-failure values. The latter may be particularly useful as an inexpensive, unambiguous way to characterize lower-bound performance of composites subjected to low-velocity impact, where the first damage to occur is intralaminar (transverse) cracks within plies that initiate due to transverse normal and interlaminar shear stresses arising from flexural and shear deformations of the loaded coupon [Maikuma 1990].

Correlating these results may be possible with a combination of instrumented impact testing data, C-scan data, and finite element analysis of the test fixture and the real structure in question. (Chapter 6 discusses use of this test method as a simple method which can be used to provide impact design data.)

3.4.1.2 Test Design

The results of the first step will necessarily drive the test strategy and test design (discussed in Chapter 5). The objective of the test design should be to provide the most relevant information about the impact resistance of the materials and material systems being considered at the lowest cost. Experimental design strategies which use a multivariate approach for describing a response function have been shown to be effective in developing the correlations of dependent variables. Examples of these are the Box-Behnken [Saczalski 1989] and Taguchi test strategies. In short, a well designed experiment will focus on the critical design criteria, response variables, and the most influential control variables.

3.4.1.3 Conducting the Tests

Upon completion of the test and experimental plan described in the preceding two sections, the test coupons are prepared and the tests conducted. Unlike conventional test programs, this methodology, coupled with the House of Quality and Pugh processes, should result in more useful information to the designer. "Design of experiments" guidelines should be used to randomize testing sequence. A detailed test plan should be included as a subtask in the project planner.

The time required to develop the test plan and to design the experiments to support it can be expected to greatly exceed that for typical trial and error test regimens; however, the extra effort spent in carefully planning the tests is likely to be rewarded many times over by the efficiency of the tests and relevancy of the results to the design problem. Clearly, the ability of the House of Quality to focus the designer's efforts on the "critical few" design parameters goes a long way in the initial stages of developing a viable and effective test plan.

3.4.1.4 Finite Element Analysis of the Impact Test Apparatus

FEA of the impact test apparatus should be performed concurrently with test design and testing. The analysis allows the designer to identify the role of the test apparatus in the impact response in terms of its contribution to energy absorption and dissipation—as a function of the apparatus compliance. This data will be used in analyzing the impact test results, allowing the designer to determine the true material response from the test. Additionally, this data will be necessary for comparing impact test results to impact events in the designed structure, allowing the test data to be used directly for design. The finite element model and analysis of the test apparatus will

become an important part of the IDM, in that once built and analyzed the results will be available for future design efforts. Details of the finite element modeling and analysis for this research are discussed in Chapter 4.

The results will be used in Phase III of the test plan to compare with structural response of the actual structure in which the material system will be employed.

3.4.1.5 Conducting Post-Test Analysis

Analyzing test results will be accomplished with respect to the response variables or "critical few" quality metrics identified in the House of Quality. These results will also be used to evaluate the various material systems proposed in the Pugh concept selection process. The results of this analysis, in conjunction with finite element analysis conducted at this stage in the Pugh process, should allow the designer to down-select to material systems which meet the design criteria as determined in the House of Quality. It may be necessary to repeat Phase 0 or 1 testing if initial results are unsatisfactory.

Feedback of the test results to the IDM is important to the dynamic development of the IDM. Its knowledge should grow along with the design team. A system should be devised for refining, updating, correcting or otherwise making changes to the sub-modules in the IDM.

3.4.1.6 Down-Selection of Material System(s)

Test results and analyses provide valuable information to the design team for down-select decisions on candidate material systems. These results may be used to support concepts developed in the Pugh process, or as an aid in refining concepts.

3.4.2 Phase II—Substructure Testing and Analysis

The purpose of Phase II testing is to select the most promising substructural components with respect to impact resistance, given a particular material system and all other design constraints. Candidates for this test phase come from the Pugh concept selection process, thus, embody the "critical few" design criteria. As in the case of materials testing, it is conceivable that the designer may wish to conduct substructure tests to support or verify conclusions developed during the Pugh process. Data previously generated and available through the IDM will be helpful in evaluating the requirements for the test plan.

The steps in this phase of the testing are similar to those for materials testing and may be performed on a parallel schedule with materials testing and analysis, allowing for a slight lag to initiate coupon tests. (See Figure 3.6.) Like coupon testing, test strategy and design are determined by the control variables to be evaluated and the response variables to be measured. Examples of the control variables which would influence impact properties of the structure are outlined in Chapter 2. They include 1) laminate stacking sequence and ply orientation, 2) stitching, 3) spar or stiffener design, 4) spar or stiffener spacing, and 5) joint design, to name a few.

3.4.2.1 Preparation of Structural Candidates for Testing

Structural candidates should be prepared and mounted in a manner which most accurately reflects the conditions under which they will be expected to perform in service. Finite element and analytical models generated in the Pugh concept selection

process for substructures and overall systems will be used at this phase of testing to compare with the results of the impact tests.

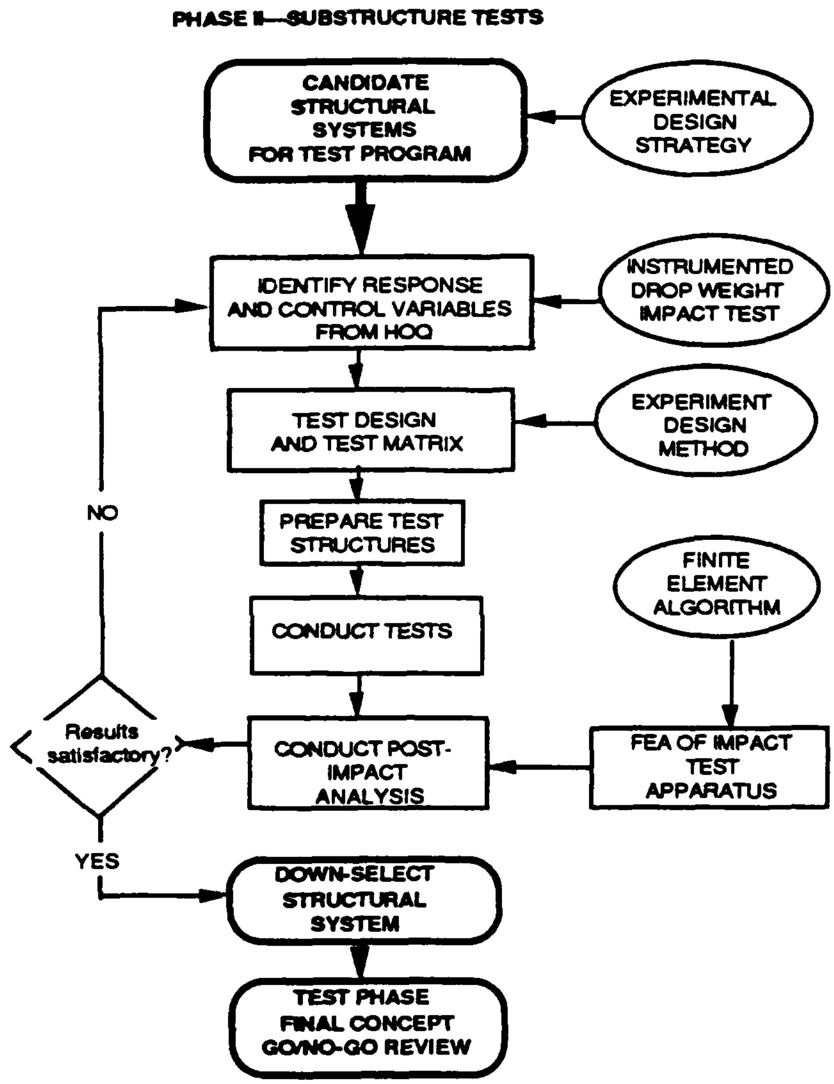

Figure 3.6 Phase II—Substructure Tests. Understanding the influence of the test apparatus and specimen support fixture is critical at this stage and may be accomplished through the use of finite element analysis. Support fixtures with easily controlled and modeled boundary conditions are desirable.

3.4.2.2 FEA of Impact Test Apparatus

Within geometric and modeling constraints—dimensional and nodal—substructure candidates can be "plugged" into the test apparatus FE model (modeled in Phase I) and analyzed for their response to quasi-static loading. These results help to further illuminate the static and dynamic behavior of components subjected to low-velocity impact. Conceptually, the impact test apparatus is modeled as a surrogate global structure for the part, albeit much stiffer than the actual structure.

3.4.2.3 Testing and Post-Test Analysis

After the tests are conducted the results will be evaluated and compared with modeling results. Refinement of the test design can be expected; therefore, it is important to minimize the number of tests required to be performed given the cost in terms of time and materials for this more sophisticated level of testing.

Response variables from instrumented drop weight impact test results may be similar to those of the material coupon testing; however, the role of structural configuration and constraint will be of particular interest to the designer at this phase of testing. It is conceivable that test results will suggest a reconsideration of the candidate materials systems, as these variables are expected to influence one another.

In comparing results of the structural response in finite element models of the test fixture with the structural response in the full-scale finite element models, the designer should begin to get some insight concerning how this part will respond to impact loading in the real structure.

3.4.2.4 Down-Selecting the Substructure

The result of this phase, if conducted in parallel with the Pugh selection process, will support specific structural recommendations for the Go/No-go review. If conducted as a follow-on to the initial candidate selection process, it will support further down-select design decisions. Regardless of sequencing of this test phase, its results and the results of Phase 0 and 1 coupon testing—in conjunction with the design data developed during the Pugh process—should result in materials and structural design solutions which are optimized in all respects, including impact resistant.

As before, feedback from the experimental and analytical results to the IDM should be included.

3.4.3 Phase III—FE Modeling and Analysis of Full-Scale Structures

The objective of this phase is to use the FE analysis of the test apparatus and the full-scale structure—in conjunction with the impact test results—to predict the impact strength of the material system and the structure as a function of bending, damage zone, energy absorption, or other response variable deemed pertinent by the foregoing analyses and tests. The relative influence of the test apparatus and the full-scale structure on the compliance of the system will be the focus of this phase.

The steps to follow in the this phase are relatively straightforward. Since most of the first order modeling and analysis of test fixtures and structures has been accomplished, the primary focus of this phase is to make sense of these analyses in terms of the actual structure and its influence on the local damage state. The motivation

is simple: to reduce or, if possible, eliminate full-scale testing of real structures for impact resistance, thus, obviating the associated costs.

Information for the first four steps of this phase, Figure 3.7, come directly from test Phases 0, I, and II and from finite element results generated during the Pugh concept selection process:

Step 1) Finite element model and analysis of test fixture—available as output from Phase I testing.

Step 2) Determine compliance of test fixture—available from Phase I testing.

Step 3) Material response from test and analysis—available from Phase I and II testing.

Step 4) Determine influence of test fixture on response—available from Phase I and II testing.

3.4.3.1 Developing a Finite Element Model of the Full-Scale Structure

By this step, a full-scale structural concept has emerged with enough detail to justify finite element modeling and analysis. The size and complexity of the structure may dictate a more sophisticated FE application such as MSC•NASTRAN; however, model generation, prepared by component, can still be easily handled in the workstation or PC environment and exported to a mini-, mainframe, or super-computer platform for compilation and analysis as needed.

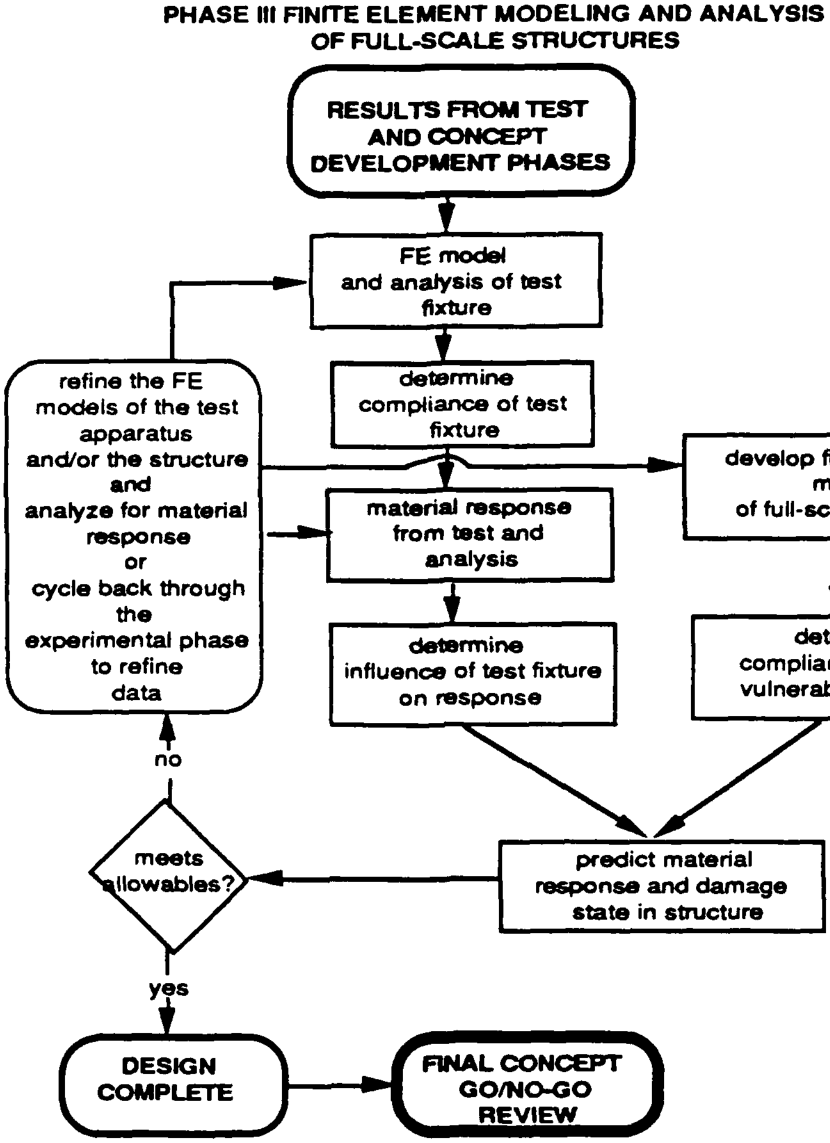

Figure 3.7. Phase III—Finite Element Modeling and Analysis. Results here provide design-decision support for final concepts, including design data for impact resistance without the expense of full-scale impact testing.

3.4.3.2 Determining the Compliance in Areas Vulnerable to Impact

Areas of the structure vulnerable to impact were determined in the House of Quality and Pugh concept selection phases. Structural responses in these areas will be determined with FEA.

3.4.3.3 Predicting the Material Response and Damage State in the Structure

The local response of the composite material in the structure will be a function of both the material properties at the lamina and laminate level as well as the structural configuration and constraints. Phases I and II assisted the development of optimum designs with respect to materials and structural systems concepts generated through the Pugh process. This step allows the designer to use the information developed in those phases to predict the impact response of these structures in a model of the actual structure.

Design allowables can be defined based on these results, by the examination and correlation of the data from these tests and analyses without the required expense and effort of full-scale structural testing. The ability to do this is critical to the development of reliable and credible composites designs which will pass muster of the user community and the regulators.

In our research we have attempted to demonstrate this approach through the investigation of the quasi-static linear-elastic case of low-velocity single impacts and a simple design criterion based on 90° strain-to-failure where global flexure and bending influence failure modes. Further application to dynamic and non-linear systems could be envisioned.

3.4.3.4 Does the Material Response Meet the Design Allowables?

If the answer to the above question is yes, the design concept is complete and the final concept decision is made. If the answer is no, two options are available to the product development team: 1) refine the finite element models of either the test apparatus or the structure, or both, and reanalyze for material response, or 2) cycle back through the experimental phase to refine the data.

3.5 Concluding Remarks about the Impact Design Methodology

This methodology is purposely general. It will require modification according to the particular application. As materials databases become more complete, it is reasonable to expect that certain tests and analyses may be unnecessary; however, each element of the framework will still require attention. The impact response of composites is very much dependent on all the structural levels—constitutive to structural configuration and constraint—addressed in the methodology as well as the impactor and its material and dynamic properties. This procedure attempts to ensure that the designer consider each of these levels and their interactions.

This methodology borrows from a number of design methods and techniques discussed in the open literature and is, in one respect, a philosophy as much as a recipe for improving impact designs. The underlying theme of both is that the challenge of designing for impact resistance in composite structures should be considered from a global point of view, based on the specific application, and in consideration of all other "design for" criteria. This methodology attempts to do just that.

Despite the inherent complexity of the low-velocity impact event, the methodology proposed for treating it is straightforward, coherent, and comprehensive—all necessary criteria for a useful design tool. While it does not offer simple solutions or a panacea cure for the design challenges impact presents, it does suggest a rational manner in which each of the collaborating factors, which influence the impact response and resultant damage state in the composite, can be systematically treated to provide reasonable design solutions in the context of real design constraints.

The development of finite element models of the impact test apparatus and representative aerospace structures, an impact test strategy and design, and other tools in support and demonstration of this methodology are the subject of the remaining chapters of this thesis. However, the IDM which supports these tools is the next topic of discussion and the final section of this chapter. It is presented both conceptually and in terms of the specific tools which comprise it.

3.6 The Impact Design Module (IDM)

The IDM is a knowledge-based expert/assistant for use by designers in addressing the design, test, and analysis issues of impact in composite materials. Ideally, it would be designed as an interactive element in a total composites structures design environment which could be invoked as needed throughout product design, manufacturing and production. This research identified a number of tools which would comprise such a module. They include, the Impact Design Methodology(Chapter 3), impact heuristics or "rules of thumb" for impact design (Appendix A); a simple to use, access and update impact reference database (written in Hypertalk® on Hypercard®); analytical and numerical tools (Chapter 4); project planning tools (Appendix C); test

procedures for assessing impact related properties at each structural level (Chapters 5 and 6); and NDE techniques most useful for detecting and assessing impact damage (Chapter 6). Updating, tailoring and revising the IDM, as demonstrated through the feedback loops in the Impact Design Methodology, is essential for its usefulness and viability. A goal of future work is to develop these tools with user-friendly interfaces and connectivity to other automated composites "design for" modules.

The subsequent chapter discusses FE tools which have been used by the author to investigate the influence of the test apparatus on the impact response in plate coupons. It is hoped that the results of this study will be useful to understanding impact testing, and will be a valuable part of the Impact Design Module.

CHAPTER 4

FE MODELING AND ANALYSIS OF THE DYNATUP MODEL 8200 IMPACT TEST APPARATUS

The model used must be the simplest one possible but not simpler.

Einstein

4.1 The Role of Finite Element Analysis (FEA) in Impact Design, Testing, and Analysis

Finite element analysis is a potentially effective design tool for gaining a quantitative understanding of a structure's response to a low-velocity impact when the complexities of the problem confound analytical solutions. However, until recently a considerable commitment of resources—time, training costs, and computer hardware and software costs—relegated its use to large aerospace, defense, and automotive firms who could afford it and required a sophisticated analysis capability. Even in these venues, FEA was typically done late in the design cycle to evaluate production intent structures or suggest improvements to problem areas shown to be vulnerable in service.

Seldom were these tools used to evaluate competing structural concepts early in design, due to their inherent costs and complexity.

Use of finite elements at the early stages in the design process, in a rather routine manner (much as one might use simple beam, plate, or shell analysis to get ball-park estimates of structural performance) is clearly desirable, yet, has only recently become feasible [Brody 1987]. This breakthrough is due to the development of easy-to-use graphical finite element modelers and FEA codes which operate on microcomputer platforms, such as the IBM PC 286/386 and Macintosh 68020/68030 computer systems. Microcomputer-based FE codes have little or no training costs (typically *the* major expense in developing an effective FE capability), and have significantly improved the FEA learning curve, provided the designer has a fundamental understanding of the problems to be solved and a rudimentary knowledge of finite element theory. Their drawbacks are limited model size, element simplicity, and, up to now, limits on the scope of problems which may be solved.[1]

In this chapter, the author will describe how a microcomputer-based FEA system has been used to model the impact test apparatus to gain insight into its structural response under quasi-static loading conditions as well as propose how this information may be used to help predict a local impact response in real structures, Chapter 7. Maximum dynamic loads from instrumented impact tests, presented in Chapter 6, are applied to models—from simple circular plates to full 3-D impact tower models—to gain a static load-deflection response, thereby determining the compliance of each model.

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[1]The FE model generator and analysis software used in this study are limited to solving static and dynamic problems with linear 2-D and 3-D elements and isotropic material properties.

Figure 4.1 reflects these issues. In short, can we model the test apparatus so as to reasonably predict its influence on the test results? If this is possible, then the impact tower can be considered as a surrogate structure (with its own unique compliance) for the design concept under evaluation.

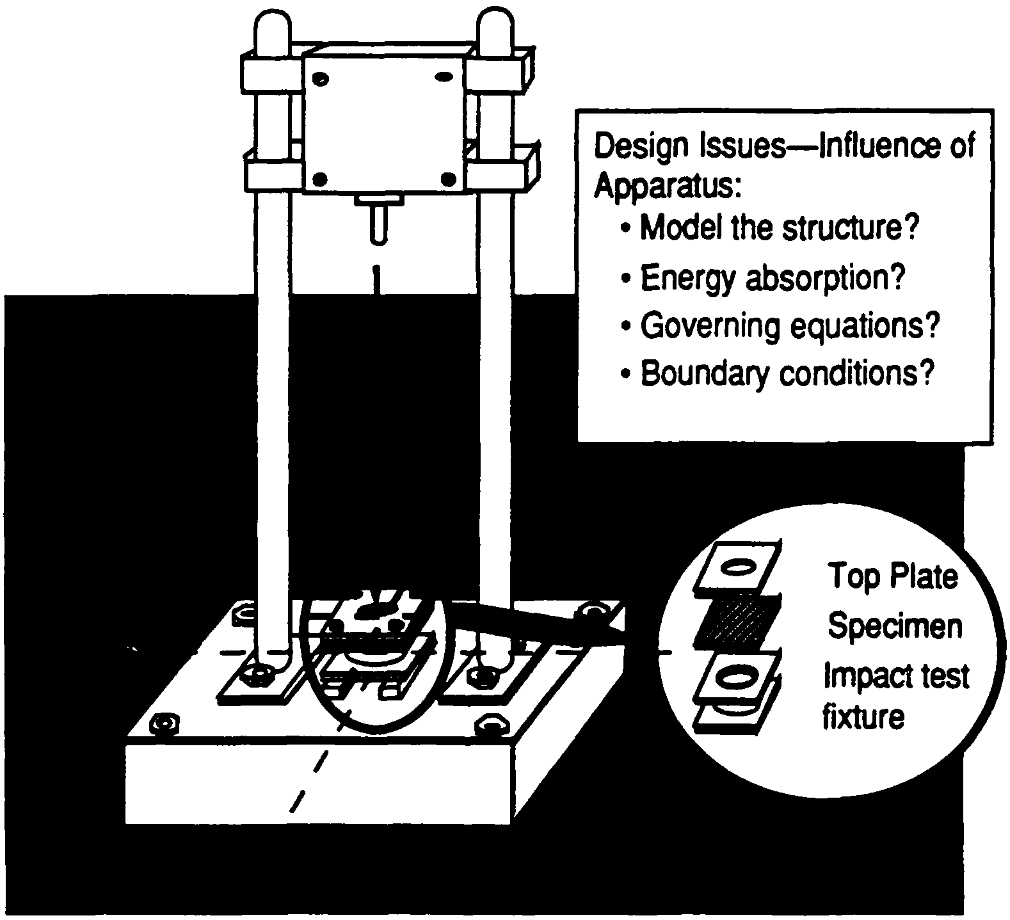

Figure 4.1 Design issues relating to FEA of impact test apparatus. Can we treat the test apparatus as a surrogate structure for our material system of interest? If so, then the issues identified in the box above must be dealt with.

4.1.1 Microcomputer-Based FEA: A Tool for Every Engineer

Microcomputer-based finite element programs have placed finite element tools in the hands of every engineer, rather than just a few finite element specialists operating complex FE software on large mainframe computers, as was the case prior to 1980 [Baran 1988]. The introduction of these microcomputer-based FE programs into the engineering market has the potential to revolutionize engineering-design methods more profoundly than did the advent of hand-held scientific calculators in the mid-1970's. The real power of these tools can be seen, not only in their speed, ease-of-use, and accuracy, but also in their ability to interface with CAD software and, through appropriate protocols, more powerful and sophisticated mini-computer and mainframe-based finite element programs. This is an important consideration as designs become more mature and/or as one needs more detail and a higher level of accuracy about system performance. While the future is now, with regard to these design and analysis tools, the development and promise of truly powerful integrated CAD/CAM systems and expert systems for design, analysis, and manufacturing offer exciting prospects for the concurrent engineering environment in the 1990's and beyond. Figure 4.2 shows the components of the FE system used in the author's work and their interfaces with personal productivity and other FE tools.

Our "customer wants" for these tools included user-friendliness, power, computational accuracy, and high speed. Exportability of finite element models, developed in LAPCAD™ (a graphical pre- post-processor) and analyzed in MSC•PAL2 (FEA application) to a mini- or mainframe platform was also an important consideration in the selection of the software. As seen in Figure 4.2, interface with MSC•NASTRAN, a commercially available general purpose FEA program, is relatively

simple. This is important when larger more sophisticated problems need to be solved, particularly, those involving anisotropic material properties and requiring non-linear elements.

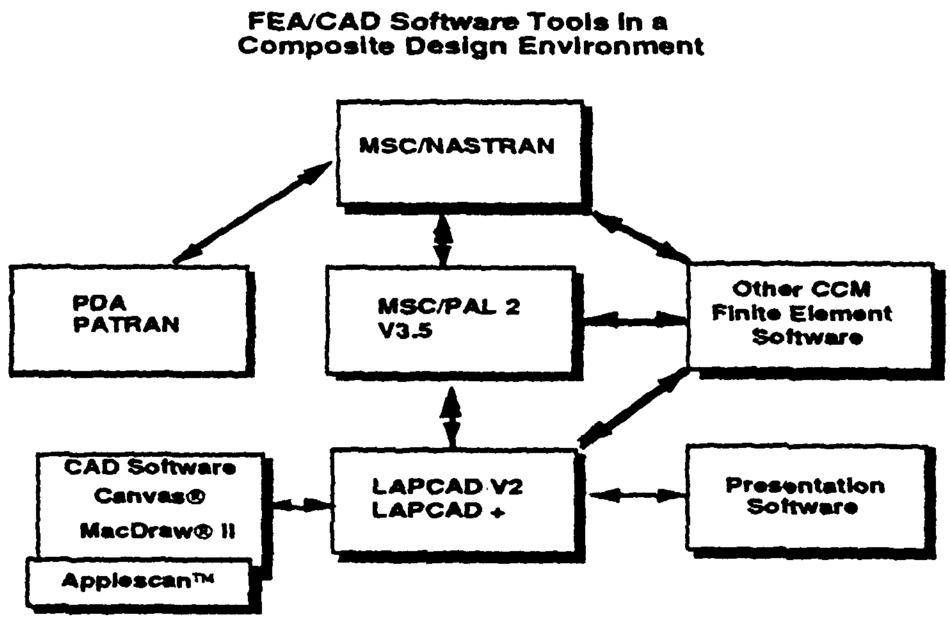

Figure 4.2 Interfaces of FEA and CAD software tools in a composites design environment. Flexibility and power leveling are important concepts for design efficiency.

The LAPCAD/MSC•PAL2 package used in this study is limited to problem sizes of 2000 nodes and 12000 degrees of freedom for static and dynamic analysis. Linear 2-D and 3-D elements, 4 types of beam elements, and only isotropic or quasi-isotropic material properties are supported, although materials files may be modified to include any, within these constraints. Details of these capabilities are provided in the

instruction manuals [MSC 1989, LAPCAD 1989]. Static—governing equation (1)—and dynamic problems—governing equation (2)—are solvable within these constraints.

$$F = [K]\{x\} \tag{1}$$

$$F(t) = [K]\{x\} + [M]\{\ddot{x}\} + [C]\{\dot{x}\} \tag{2}$$

Here F is the force, F(t) is time dependent force, [K], [M], and [C] are the reduced/discretized stiffness, mass and damping matrices, respectively, the sizes for which depend on the number of active degrees of freedom in the model. The relationships for displacement, $\{x\}$, and its second and first time derivatives for acceleration and velocity are shown in equation (2). Problems involving enforced loads, for example, are solved for displacement at each nodal point and stresses are calculated from these solutions. Results can be viewed graphically on model contour plots and wireframe animation and through a hierarchy of tabular output.

The limitations with respect to material properties and element type were not of initial concern in this research, since their primary use was to statically analyze the Dynatup Model 8200 test apparatus and specimen support fixtures (composed of isotropic materials) to determine the respective compliance of each. Plate analysis of composite quasi-isotropic laminates, without consideration of Hertzian contact deformation, was also possible with this package.

Some helpful guidelines and heuristics on the use of finite elements in this routine way are presented in Appendix D. These were compiled from a book by Baran

[1988] about PC-based FEA; personal experience, developed through the use of LAPCAD II; and from Segerlind's [1976] discussion of FE theory and application.

A Macintosh IIx (MC 68030 microprocessor) CPU configured with 8 MB of RAM, 180 MB of storage, and a full color 20 inch Radius® monitor with video card and 32 bit color Quickdraw®, provided a satisfactory platform to operate the software.[1]

4.1.2 A Finite Element Algorithm for the Impact Design Methodology

Before discussing the modeling and the analysis of the impact tower, the author would like to devote some time to the presentation of a simple model which could be used in the impact design methodology to evaluate competing concepts using finite elements and, in this study, for determining the compliance of the impact test apparatus.

The philosophy behind the development of this algorithm is that finite elements, in the hands of a prudent and judicious product design team, can provide valuable insight into structural behavior of preliminary design concepts early in the design process, despite the lack of specificity which may exist at this stage of design regarding configuration, materials, in-service loads, and boundary conditions. The resulting compliance of the structure to be evaluated, is important to the designer; assuming the ability to correlate its material response the with material response in the test fixture apparatus, discussed in Section 4.3.

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[1]The author's personal productivity software, graphics software and Apple® grayscale scanner made up the remainder of the system, providing the flexibility to build and analyze models, evaluate results, and produce reports with relative ease.

This general modeling approach is recommended for building models from component to system level and from simple to more complex systems. It should be obvious that to build more precision into the model than one's understanding of the loads, boundary conditions, and target response is at once unnecessary and unproductive. Refinement of the model is accomplished as one becomes more confident of the factors cited above.

The process is presented in two phases: 1) Phase I—Simple model geometries of the components of the structure are developed and analyzed according to the required degree of accuracy and based on the knowledge of the real structure, Figure 4.3, and 2) Phase II—System models are developed from the individual components developed in Phase I. As in Phase I, models are refined and optimized to provide information for the decision-making process.

4.1.2.1 Phase I—Component Level FE Modeling

FE modeling and analysis guidelines and the reporting procedures, discussed in Appendix D, should also be followed. With these points in mind, a step-by-step discussion of the process is presented. The following steps correspond to the numbered boxes in Figure 4.3:

Step 1) Create Simple Model Geometry (Components)

During the evaluation of structural concepts in the Pugh Selection Process component models are developed and analyzed for static and/or dynamic loads. Models should be generated as follows:

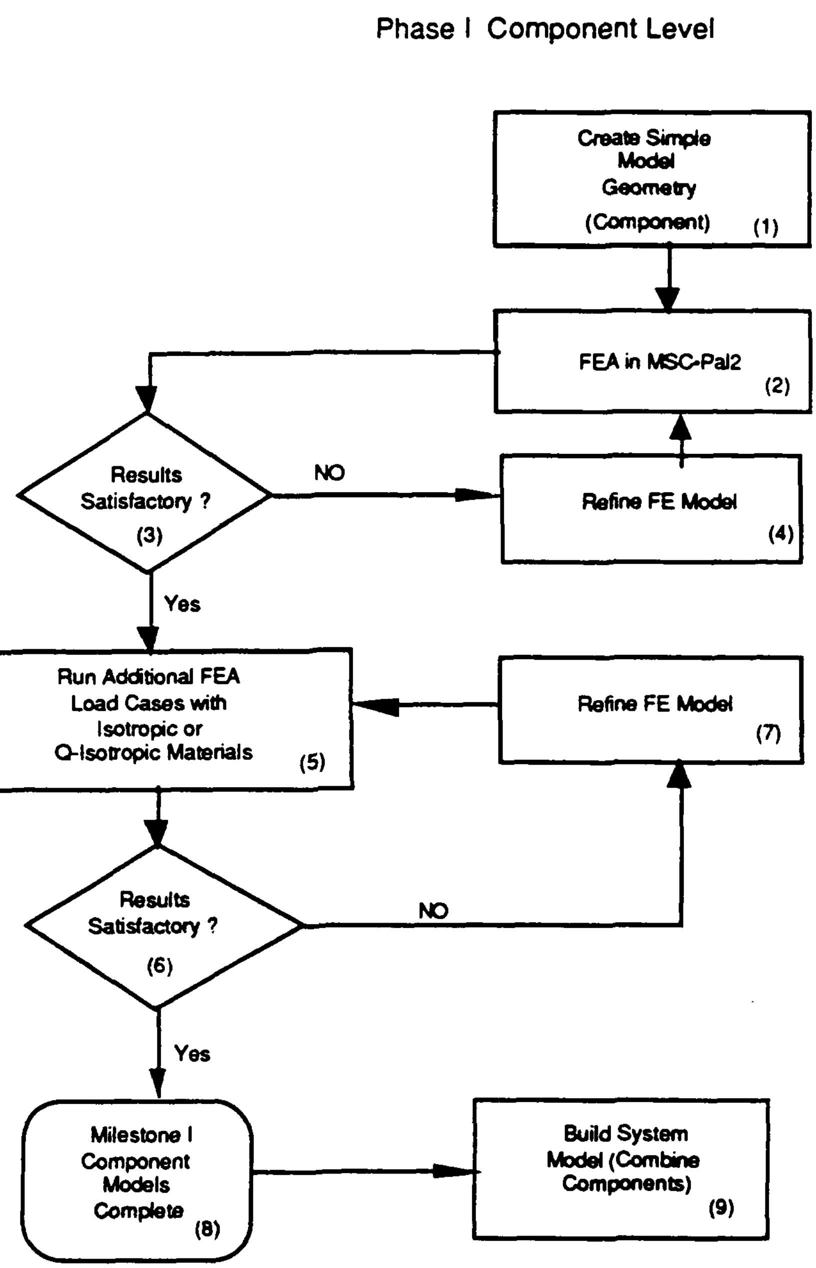

Figure 4.3 Phase I of the finite element algorithm results in viable component level concepts for the product. Sec..ntial modeling as shown here may not always be the best approach. The resources available to conduct FEA may suggest a simultaneous approach, i.e., component and systems level.

a) Model geometry may be generated in a variety of ways. During our analysis of the impact tower, finite element meshes of tower components were created in LAPCAD II. Additionally, scanned drawings were exported to LAPCAD II in PICT file format and finite element meshes were generated. Material properties were also assigned at this point in the modeling. Since LAPCAD II handles only isotropic material properties, quasi-isotropic composite properties may be used to represent a lower bound for the model where composites are being considered.

b) After model geometries are developed, loads and boundary conditions are assigned. Again, this is done graphically in LAPCAD II. LAPCAD II builds two files: one for model geometry and one for loads and boundary conditions.[1]

Step 2) Finite Element Analysis in MSC•PAL2

It is prudent at this step to run a static analysis of each component model generated in Step 1). Simple cases should be performed first to check the integrity of the model and the accuracy of the results. Once satisfied that the model is accurate and the results are reasonable, one can proceed to refine the model.

Steps 3) and 4) Model refinement

[1]The most difficult aspect of this step proved to be selecting loads and boundary conditions which represented real physical behavior; it is important to recall that precision in selecting these conditions should be commensurate with one's understanding of real structural behavior.

If the results of the analysis are satisfactory, one may proceed to Step 5), if not, return to Step 4) and refine the model geometry, loads, and boundary conditions as appropriate. Convergence techniques may be employed [Segerlind 1976]. Identification of stress concentrators [Wilkins 1983], particularly detrimental to impact properties, may be identified through these steps. Insight into structural response is the primary objective. First order results will generally be acceptable given that this analysis is performed early in the concept evaluation process for the purpose of evaluating competing concepts which are likely to be quite general.

Steps 5), 6), and 7) Run additional FEA load cases with isotropic or quasi-isotropic materials, evaluate, and refine the model

This cycle of steps is similar to Steps 2), 3), and 4) with the exception that the focus of refinement is on addressing a variety of load cases and material properties which might represent a lower bound of performance for the component being studied. In the case of the impact tower, the component geometry and material properties were known; therefore, the focus of these steps was modification of the test specimen parameters, loads, and boundary conditions. In product design, one would desire a fundamental understanding of the structural response, given particular materials system concepts which are being evaluated for impact resistance.

Step 8) Milestone I—Component Models Complete

This is the major milestone of Phase I. At this point, reasonable component models should exist which can be combined in Phase II to produce system models. One should have files on each of the models which support decisions made to change or eliminate certain concepts of components or material properties. The concurrent selection process for materials systems, manufacturing process, etc., will provide input to the design throughout this modeling and analysis process. The design problem defined at the beginning of the product development process will largely determine the scope of the finite element analysis and the sequence of model development and analysis.

4.1.2.2 Phase II—System Level Modeling

The steps for the system level modeling are presented below, corresponding to the numbered boxes in Figure 4.4.

Step 9) Build System Model

The component models developed in Phase I are connected into a system level model. The size of the model (nodes and elements) should be calculated before attempting to build the system to insure it will not exceed the nodal limits of LAPCAD II and MSC•PAL2 (2000 nodes). If the model is too large for LAPCAD II and/or MSC•PAL2 and cannot be reduced in size, it can be exported to MSC•NASTRAN in Bulk Data File (BDF) format and combined there for analysis. (Model modification with fully anisotropic properties could be accomplished at this point, as well.)

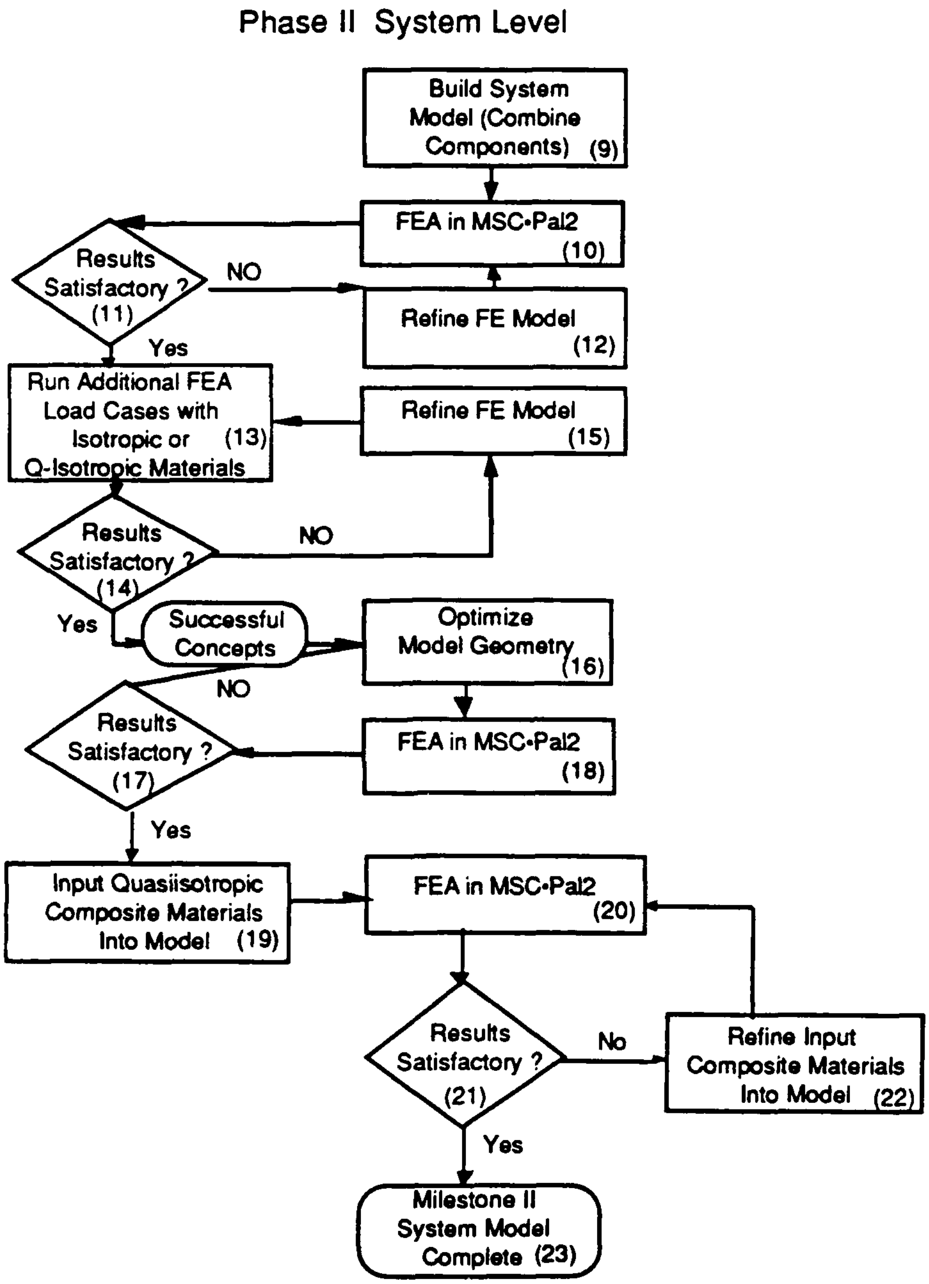

Figure 4.4 Phase II of the finite element algorithm results in systems level analysis of structural concepts.

Steps 10), 11), and 12) System level analysis and refinement.

The same points made in the discussion above [Steps 2), 3), and 4) in Figure 4.3] apply at the system level. Again, model size must be monitored. It is easy to develop a "forest for the trees" mentality during this phase of the modeling. This may be detrimental to the objectives of selecting concepts and determining structural locations which may require more attention during detailed design and analysis. A general "rule-of-thumb" is to limit oneself to one or, at most, two iterations of refinement once a convergence trend in the results is identified. Quick turnaround is essential if these tools are to be of value at this stage in the product development process.

Steps 13), 14), and 15) [See Steps 5), 6) and 7) in Figure 4.3.]

Since a level of model development and refinement was accomplished in Phase I at the component level, the focus should be toward identifying future opportunities for applying the flexibility of composites and impact resistant techniques and eliminating concepts. (In modeling the impact test apparatus these steps were unnecessary; therefore, they were not performed.)

Steps 16), 17), and 18) Model optimization

Because of time and other resource constraints it is likely that additional model optimization would be conducted only on the remaining one or two concepts. Structural optimization would be the objective at this stage. All preceding comments on model refinement apply.

Steps 19), 20), 21), and 22) Final optimization cycle

The remaining concept(s) (recall we are also competing with the benchmark) are refined initially to quasi-isotropic material properties and secondly, to fully anisotropic material properties, in a full-featured FEA program, such as MSC•NASTRAN. Step 22) may be postponed until some later stage in product development, for example, after materials testing or during prototype development.

Step 23) Milestone II System model analysis complete

At this stage, the finite element analysis techniques in conjunction with the other concept evaluation tools have been applied in a disciplined manner to the development of one or, at most, two promising concepts. These would likely be presented at a go/no-go review for a decision on further development and testing. For this reason, it is imperative that the concept evaluation process be well documented in a concise and unequivocal manner which supports the team's recommendations. Development beyond this step is shown in the design methodology.

4.1.2.3 Some Final Notes on the Finite Element Algorithm

It is worth reiterating that the general FE algorithm described above is best considered as a flexible and tailorable tool in the engineer's "tool kit." Rigid application of this algorithm, or any of these tools, defeats their purpose, which is to provide design guidance and information at a level commensurate with engineering challenge at hand. Results should be approached cautiously and, whenever possible, verified through independent analysis and testing. Tradeoffs and design decisions based on

experience and heuristics should be given equal weight, particularly with respect to impact resistance, and contradictory results verified through additional analysis or testing. Using this technique, appropriately modified, we demonstrated its efficacy in modeling the impact test tower; the description and results of which are presented in Section 4.3.

4.1.3 Impact Tower as Structural Surrogate

In this study, rather uniquely, the impact test machine has been viewed as a structure with its own unique set of physical properties and mechanical responses to imposed forces and moments. It was reasoned that this set of properties would contribute to the impact response of the test coupons according to the mass, stiffness and damping of the individual components through which the load was transferred. Of interest to the author, was to accurately model the impact test machine (much as one might model an airplane wing or fuselage) and to impose loads on it which were representative of those that it would see during the impact event. In this way, the influence of the impact tower could be compared directly with the influence of real structures in a low-velocity impact where assumptions of quasi-static loading are valid [Zukas 1982, Elber 1983, 1985]. The loads used in the modeling were based on the maximum dynamic loads of the impact tests conducted.[1] A complete physical description of the Dynatup impact test machine, including dimensions, shape, and material properties, was written into an Excel spreadsheet for recall during the modeling

[1]Nearly 8 kn (1800 lbs.) loads were generated in the 40 Joule tests of the 48 ply AS4/3501-6; however, a 4.5 kn (~ 1000 lbs.) was used in the modeling. This was approximately the maximum load generated in the 32 ply APC-2 with a 6.08 cm annulus in the test fixture.

process in LAPCAD II, and is an appendix to the CCM Supplement to the Dynatup Model 8200 Operator's Manual [Lindsay 1990b].

As a system of masses and springs, the tower, support fixture, and test coupon will respond to an enforced displacement (or load) in a linear-elastic manner[1], if a quasi-static response is assumed up to the incipient damage point. This comparison of the static and quasi-static response and associated governing equation are represented in Figure 4.5.

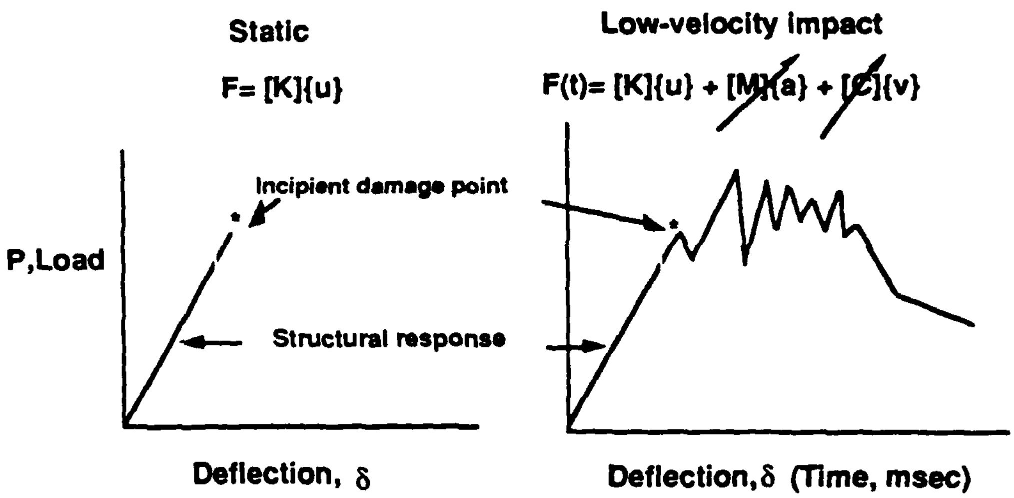

Figure 4.5 Comparison of load-deflection response under a static force vs. a time dependent force with applicable governing equations. In a low-velocity impact event the inertial terms and damping terms may be neglected as a reasonable approximation of the system response.

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[1]Damping influences were neglected in this study due to the difficulties in quantifying them for a structural system as complex as the impact tower with specimen. These effects become much more important at higher velocities as has been shown by the ability of aramid fibers to provide excellent ballistic impact resistance due to good vibrational damping properties and high strain to failure [Dupont 1981].

In a simple way, the impact tower can be represented as a structural surrogate for the structure being designed. Each component will contribute to the impact response according to its material properties, configuration, and the boundary conditions imposed on it. As will be described in Section 4.3, the response of the tower components can be quite interesting. Significant variations in test results can be expected with changes in the test apparatus—installation and setup—beyond those which are predictable by plate analysis, changes in test fixtures, or coupon boundary conditions. Identifying the compliance of the components in the structure (and the test apparatus) should allow one to predict their respective response in models with representative loading conditions. Figure 4.6 represents this notion of the impact tower as structural surrogate.

While this may oversimplify the point, one could envision an approach that will take these compliances into effect in both structures to get the local impact response as a function of the known (or predicted) impact energy, resultant load contribution and deflections, and, finally, the stress and strain state in the structure at that point.

Allowing for variations in response due to the specimen support fixture (addressed in Section 4.3.3) the remainder of the test apparatus used in this study was shown by FEA to be exceedingly rigid (relative to the test coupons), contributing little as an impact energy absorbing mechanism. If, however, one conducted a thought exercise and placed the impact tower on a base of very compliant material, say Jello®, it would be immediately apparent that the first "spring" responding in this model would be this "Jello" base regardless of where the load was applied.

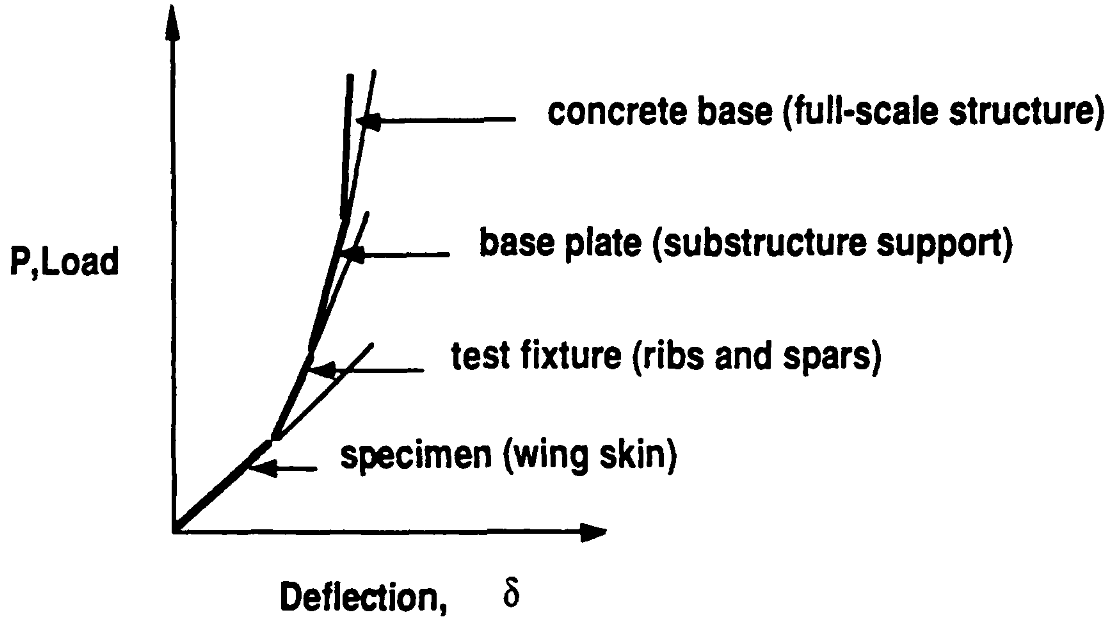

Figure 4.6 A component by component comparison of a impact test fixture and a real structure. The most compliant (weakest spring) component in the load path will respond to the load first. The stiffer the substructure the less it contributes to the load-deflection response. In the case of a composite wing skin under bending and/or contact deformation, if local stress (developed by the total load) exceeds local strength, the composite "breaks."

More realistically, one could visualize this in the way a real structure might respond to an impact. For example, consider a composite helicopter maintenance access door, opened and supported like a cantilever plate; the local impact response to a tool dropped at the end of the door, where bending compliance is greatest, would be expected to be less severe than from the same tool dropped at or near the hinged end, where a much stiffer global response is anticipated. Examining the resultant damage from the two tool drops would reveal more loc ., internal laminate damage in the form

of microcracking, and, if energy levels were high enough, delaminations, fiber breakage, debonding, etc., in the latter scenario. This is because work done (energy absorbed) in plate bending is not available in the latter case.

A simplified scenario, such as this, suggests that the structural configuration and constraint, whether in a real structure or in a test machine, must be considered when evaluating the material response for design purposes. It also suggests that impact test results may be conservative estimates of the impact strength of a material due to the inherent rigidity of the typical test apparatus. However, it must also be kept in mind that these tests are normally conducted with no preloads on the coupon and at room temperature conditions which infrequently represent actual service conditions.

As a prelude to investigating the load-deflection response of the test apparatus in a static analysis, a review of circular plate analysis for isotropic and orthotropic plates was conducted to verify the accuracy of the FEA software, and as a check against the analysis to be done later with models of the Dynatup test fixture and the test results.

4.2 Theoretical Development for a Circular Plate Subject to Point Static or Impact Loads

Before looking at the more global problem of modeling the impact tower structure, it was deemed useful to consider the problem of a circular plate subject to a point load, as this most closely represented the impact event using the Dynatup specimen support fixture and a blunt impactor tup. The author planned to compare the analytical results with finite element results from MSC•PAL2 for the cases of 1) a clamped circular

plate and 2) a simply supported plate. These results would then be compared with static-load deflection tests of aluminum plates of thickness 0.312 cm (0.123 in.) conducted using the apparatus described in Chapter 6. This simple analysis would determine the accuracy of the FEA program as well as underscore the difficulty in applying analytical or numerical solutions with idealized boundary conditions to real structural problems.

4.2.1 An Overview of Force-Deformation Analyses of Thin Plates

The first step in this exercise was to examine the forces which contribute to plate deformation. According to Bostaph and Elber [1982] a strength of materials formulation was shown to adequately predict the deformation of thin plates (up to 32 plies). The total load-displacement relation for these plates showed that one may get the total displacement for a point load by summing the mid-plane deformation from the shear and flexural deformations with the deformation due to indentation. Figure 4.7 represents these various forces and the load-displacement equations governing them. Initially, the author considered the contribution of the Hertzian force which causes indentation deformation.

The indentation load (total load), P, is obtained by summing the point load, P_P, and membrane reaction load, P_M[1]. This load provides the Hertzian indentation deformation, δ_I, according to the Hertz law [1881] shown in Figure 4.7 and Equation

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[1]Bostaph and Elber [Bostaph 1982] have shown in static indentation tests that for 8 ply (thin) laminates, where the plate displacement exceeds the plate thickness, membrane actions due to mid-plane stretching must be analyzed. They concluded that while initial delamination is matrix shear strength dependent, the pure membrane failure mode controls plate penetration after delamination, and that membrane failure energy depends only on ultimate fiber strain and fiber modulus. The author's test results showed little dependence on membrane effects.

(3). The target and the impactor are assumed linear elastic, and the impact is normal to the surface. Since the contact duration between the impactor and the target in low-velocity impact is very long compared with the natural frequencies of both, Rayleigh [1906], vibrations of the system are neglected and the static Hertz force, P, is the total force

$$P = K_I (\delta_I)^{3/2} \tag{3}$$

where the coefficient, K_I, is dependent on the radius of the impactor, R_1, and material properties—Young's modulus, E, and Poisson's ratio, υ,—of the impactor and target according to equations (4), (5) and (6) for isotropic materials.

$$K_I = \frac{4\sqrt{R_1}}{3\pi (k_1 + k_2)} \tag{4}$$

$$k_1 = \frac{1-\upsilon 2}{\pi E_1} \tag{5}$$

$$k_2 = \frac{1-\upsilon 2}{\pi E_2} \tag{6}$$

Greszczuk [Zukas 1982] has shown that the maximum indentation deformation, δ_I, occurs when $\dot{\delta}_I = 0$, i.e., velocity is zero, and is given by equation (7).

$$\delta_I = \left(\frac{5v^2}{4MK_I}\right)^{2/5} \tag{7}$$

where v is the approach velocity of the two bodies at time, t = 0, i.e., at incident impact and M is the sum of the inverses of the masses of the target and the impactor.

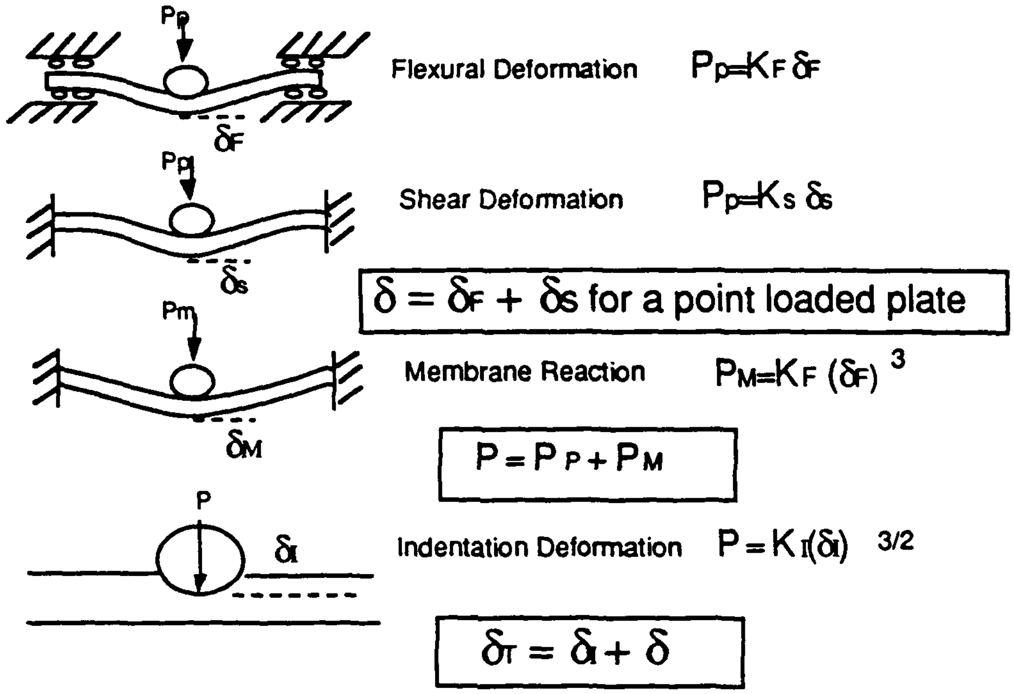


Figure 4.7 A force/deformation model superposition for thin plates analyzed under quasi-static loading conditions [Elber 1983]. This shows the force contributions to the total from point and membrane loads as well as the total deformation composed of the flexural, shear and indentation deformations.

Alternately, an energy balance approach can be used to find the contact deformation assuming a stationary semiinfinitely thick target and impactor with velocity, v_1. The incident impact energy is the kinetic energy of the impactor with mass, m_1, and the relationship with the impact force and displacement is obtained simply by integrating over the force-displacement curve

$$K.E. = \frac{1}{2} m_1 v_1^2 = \int_0^{\delta_I} P\, d\delta \tag{8}$$

Substituting equation (3) into equation (8), evaluating the integral and solving for δI gives the same result as in equation (7). In this situation, v_1 is equivalent to v and M is equivalent to $1/m_1$. Finally, Greszczuk gives the equations for impact force, radius of the area of contact, and magnitude and distribution of surface pressure in terms of impact velocity, geometry of the impactor as well as the elastic properties and masses of the impactor and the target. These all are of interest in the analysis of the impact event.

If the target is transversely isotropic, the expression for k_2 changes from the simple one in equation (6) to the much more complex expression

$$k_2 = \frac{\sqrt{A_{22}}\left\{\left(\sqrt{A_{11}A_{22}}+G_{zr}\right)^2 - \left(A_{12} + G_{zr}\right)^2\right\}^{1/2}}{2\pi\sqrt{G_{zr}}\left(A_{11}A_{22} - A_{12}^2\right)} \tag{9}$$

where

$$A_{11} = E_z\ (1-\upsilon_r)\beta$$

$$A_{22} = \frac{E_r\ \beta\left(1-\upsilon_{zr}^2\,\omega\right)}{1+\upsilon_r} \tag{10}$$

$$A_{12} = E_r\ \upsilon_{zr}\,\beta$$

$$\beta = \frac{1}{1-\upsilon_r - 2\upsilon_{zr}^2\,\omega}$$

$$\omega = \frac{E_r}{E_z}$$

and E, G, and υ are the Young's modulus, shear modulus, and Poisson's ratio of the target, and the radial and through-the-thickness directions are denoted by the subscripts r and z, respectively. (A similar expression would exist for k_1 if the impactor was anisotropic.) In the case of the 16 and 32 ply quasi-isotropic coupons used in this study, the in-plane properties, r, are independent of orientation. Greszczuk [1975] has shown that the z direction (direction of impact) properties are those which influence k_2 the most. For a unidirectional laminated composite, such as those used in this study, where $E_z << E_{impactor}$ (if the impactor is rigid), the matrix properties can be used as a first order approximation to determine k_2 since they dominate the z direction properties, thus, the indentation deformation. Greszczuk [Zukas 1982] notes that the value of k_2 for a generally orthotropic material can be obtained experimentally from a static indentation test. Through these expressions and some experimental work, δ_I can be obtained for a range of loads. Deviation from the theoretical predictions will result at some load level (depending on the matrix properties) due to the inelastic deformation of the target.

In our problem, however, we were interested in the total force deformation response typical of a flexible plate target, both isotropic and anisotropic. Since our target is neither stationary nor semiinfinite, we considered the other force contributions identified in Figure 4.7. The isotropic case was studied by Goldsmith [1960], and the anisotropic, both analytically and experimentally, by Greszczuk and Sun [1975]. For a flexible plate-type target (like those in this study) the surface pressure, area of contact,

and impact duration will be a function of the physical and dynamic properties of the impactor, velocity, and material properties of the target; additionally, plate bending stiffness and the boundary conditions now come into play. As noted by Greszczuk [1982], "for a given impact velocity the magnitude of dynamic force, P, will decrease as the target flexibility increases (or thickness decreases). Increase in target flexibility will also increase contact duration and decrease the area of contact." The results of the impact tests given in Chapter 6 show this to be the case.

An approximate solution to the total deformation, $\delta_T = \delta_I + \delta$, of a thin plate includes the contributions of the Hertzian force-deformation and the plate bending force-deformation shown in Figure 4.7 given by the expression

$$P_p = K_p \, \delta_p \tag{11}$$

where Kp is the spring constant for the plate which will be a function of the material properties of the plate, dimensions and boundary conditions. If the plate is stationary then the energy balance for the total system is

$$\tfrac{1}{2} m_1 v_1^2 = \int_0^{\delta_{max}} P_p \, d\delta_p + \int_0^{\delta_I} P_c \, d\delta_I \tag{12}$$

where the second term on the right hand side of (12) is from equation (8), the contact energy, and the first term is the plate bending term. As shown by Greszczuk and Elber given that $P = P_p = P_c$, the following expression for the energy balance is obtained after substitution of (11) and (3) into (12) and evaluation of the integrals.

$$\tfrac{1}{2}m_1v^2 = \frac{1}{2}\left(\frac{P^2}{K_p}\right) + \frac{2}{5}\left(\frac{P^{5/3}}{K_I^{2/3}}\right) \tag{13}$$

As seen previously, K_I depends on the material properties of both impactor and target according to the expressions for k_1 and k_2. For transversely isotropic materials, the target's contribution through k_2 will largely depend on the *z* direction properties which are dominated by the matrix, equation (9). The plate bending term, on the other hand, will depend exclusively on the in-plane, *r*, direction properties, which for a quasi-isotropic lay-up are the same in the 1 and 2 directions. Plate bending expressions, equations (14) and (15), for K_p and K'_p for a circular isotropic or quasi-isotropic composite plate of radius, R, and thickness, h, clamped or simply supported along the outer boundary are given by Roark and Young [1975].

a) clamped plate

$$K_P = P/\delta = \frac{4\pi E_r h^3}{3\left(1-\upsilon_r^2\right)R^2} \tag{14}$$

b) simply supported plate

$$K'_P = P/\delta = \frac{4\pi E_r h^3}{3\left(1 - \upsilon_r\right)\left(3 + \upsilon_r\right)R^2} \tag{15}$$

For the case of the clamped circular plate it can be shown that the total force energy balance, including plate bending and Hertz contact deformation effects yields the following expression:

$$\frac{1}{2}m_1v^2 = P^2\left[\frac{3\left(1-\upsilon_r^2\right)R^2}{\delta\pi E_r h^3}\right] + P^{5/2}\left\{\frac{2s}{5}\left[\frac{3\pi\left(k_1' + k_2'\right)}{16\sqrt{C_R}}\right]^{\frac{2}{3}}\right\} \tag{16}$$

where C_R and s are terms which take into account the curvature effects of both the target and impactor. Values for s are given for various angles, θ, by Greszczuk [Zukas 1982].

Greszczuk further develops this theory to consider time effects in terms of impact duration; and determines internal stresses caused by the impact pressure, knowing the surface pressure, its distribution, and the area of contact, all as a function of impact velocity and time. The time-dependent internal triaxial stresses in isotropic, multilayered orthotropic, or anisotropic targets can be determined using various FE codes. (An ANSYS code was used by Greszczuk.) The final step in Greszczuk's approach is to establish failure modes for the internal triaxial stresses caused by impact-induced surface pressure. The time sequence for these failure modes can also be determined. A distortion energy theory, which allows for determination of a failure envelope within which failure has occurred due to interaction of multiaxial stresses, has been used by Greszczuk and Sun [1975]. He presents results for a variety of cases showing how failure modes are influenced by fiber and matrix properties, fiber orientation, stacking sequence, and target thickness.

Generally speaking, the locations of maximum stresses under surface loading (Hertz contact force) can be predicted by this technique. Figure 4.8 shows where maximums exist for these through-the-thickness stresses from indentation forces. Plate bending effects produce top surface compressive and back surface tensile stresses as well as internal shear stresses, also shown in Figure 4.8.

The results of these stresses on failure modes can be clearly seen in the photomicrographs presented in Chapter 6. In the case of plate bending effects, a failure criteria based on maximum stress or strain allows one to predict tensile failure transverse to the fiber direction, $\varepsilon_{90°}$, tensile fiber failure, $\varepsilon_{0}°$, interlaminar shear failure or compression failure in either the 1 or 2 direction. For thin plates—and impacts far from stiffeners in real structures—it is these plate bending effects which dominate the stress and strain states; therefore, the designer should use $\varepsilon_{90°}$ as a first order estimate for incipient damage (keeping in mind the membrane action contribution for very thin or large plates). For thick plates—impacts in areas where bending is suppressed (such as directly on top of a spar or stiffener)—the Hertzian contact force likely dominates.

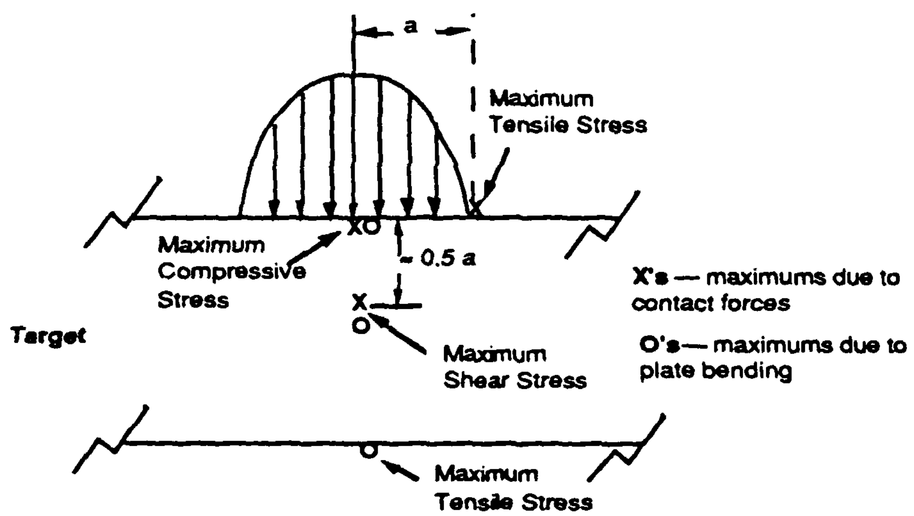


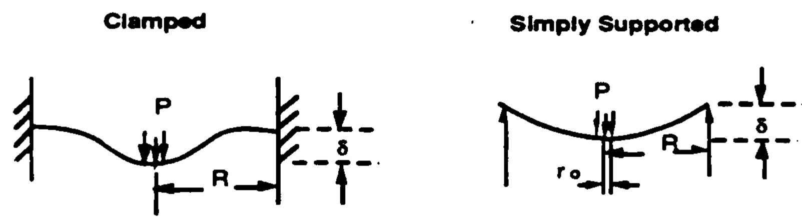
Figure 4.8 Contact and plate bending maximum stresses through-the-thickness of a plate due to a sine wave surface loading caused by a spherical impactor impinging the target normal to its surface (after Greszczuk [Zukas 1982]. Whether the plate fails in bending or due to Hertzian forces is dependent on the impact pressure, plate thickness, and structural configuration.

In this study, focus was on the linear-elastic mechanisms up to the incipient damage point, since it is these mechanisms which the designer must understand first to approximate when damage will occur in real structures. The theoretical basis for the obvious mechanisms, plate bending and contact deformation with idealized boundary conditions, was presented above and provided a good spring board for evaluating the accuracy of the FE program which would be used to investigate the less obvious contributing mechanisms, structural compliance.

The following two sections show the results of a simple analysis of circular isotropic plates of dimensions equivalent to those used in the static-load deflection experiments. Comparison with those experimental results is also presented and will be reassessed in Chapter 7.

4.2.2 Analytical and Numerical Solutions for Circular Plates

Figure 4.9 presents solutions for the two cases—clamped and simply supported—for a circular isotropic plate;



$$\delta = \frac{-P\,R^2}{16\,\pi\,D}$$

$$\delta = \frac{-P\,R^2\,(3+\nu)}{16\pi\,D\,(1+\nu)}$$

Figure 4.9 Solutions for determining the maximum deflection, δ, in a circular isotropic plate under a point load Roark and Young [1975].

where R is the radius of the plate, δ is the maximum deflection, P is the total applied load, υ is the Poisson's ratio, and

$$D = \frac{Eh3}{12\,(1-\upsilon^2)} \tag{17}$$

where E is the Young's modulus and h is the plate thickness. These solutions are the same as equations (14) and (15) solved for δ. For our problem we used the following values for an aluminum plate 0.312cm (0.123 in.) thick with radius 6.35 cm (2.5 in.): 1) E= 69 Gpa (10 msi) and 2) $\upsilon = 0.33$.

A finite element model of this plate was also built using linear quadrilateral and triangular plate elements and analyzed in MSC•PAL2. Figure 4.10 is a model showing the boundary conditions for the clamped case and one loading case, 622 N (140lbs.). A series of static load cases was run to compare directly with the experimental static load-deflection tests.

Equations (14) and (15)—also those shown in Figure 4.9—were solved analytically for the same loading cases. FE and analytical solutions were then compared. The two solutions were in agreement indicating that 1) the FE algorithm is adequate for this problem and 2) the model definition, mesh size and composition, and the loads and boundary conditions are accurate. The graphical mesh generator and menu driven analysis software greatly simplified model preparation and refinement. Hertzian contact deformation is not taken into account in either the analytical or numerical solutions, however, tests will record these contributions.

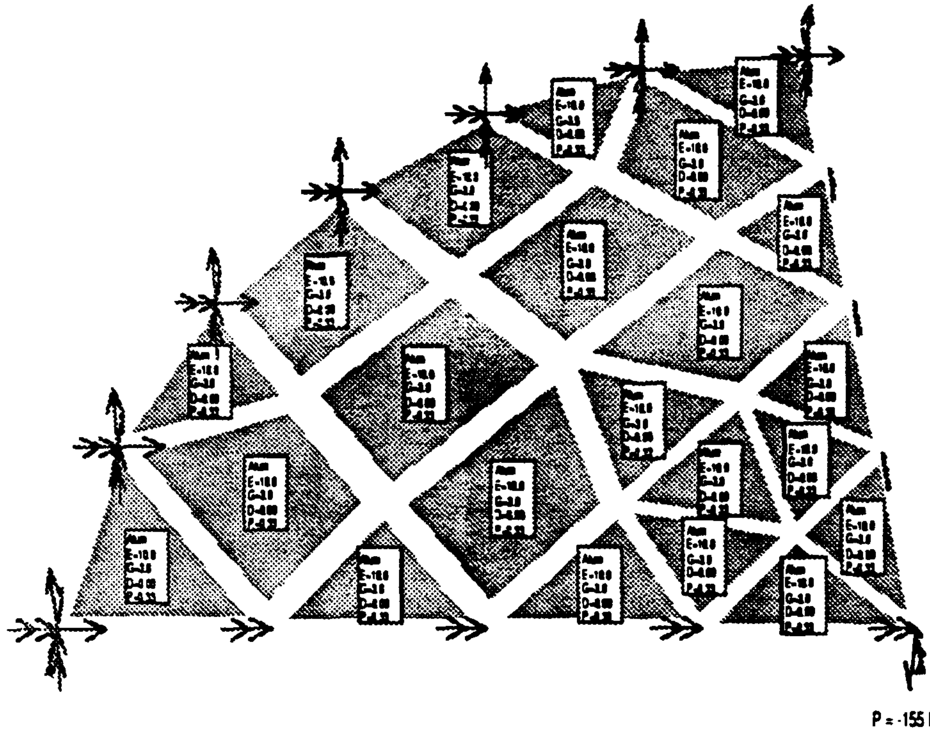


Figure 4.10 FE model of a clamped circular aluminum plate—0.312 cm thick and 6.35 cm dia.—subject to a point load of 622N. [1]

Using equation (3), (4), (5) and (6) the contact deformation for the aluminum plate under a variety of loads by a 12.7 mm (0.5 in.) diameter steel tup was calculated. The Hertzian contribution to the total deflection response is presented with

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[1]Only a quarter model was necessary due to symmetry conditions. Therefore, the load applied to the center node represents 1/4 of the total load, P, given in the closed form solution by Roark and Young. Use of triangular plate elements was kept to a minimum.

the other contributions in Figure 4.11. Obviously, the experimental results show considerable more deflection even when the Hertzian contribution is accounted for.

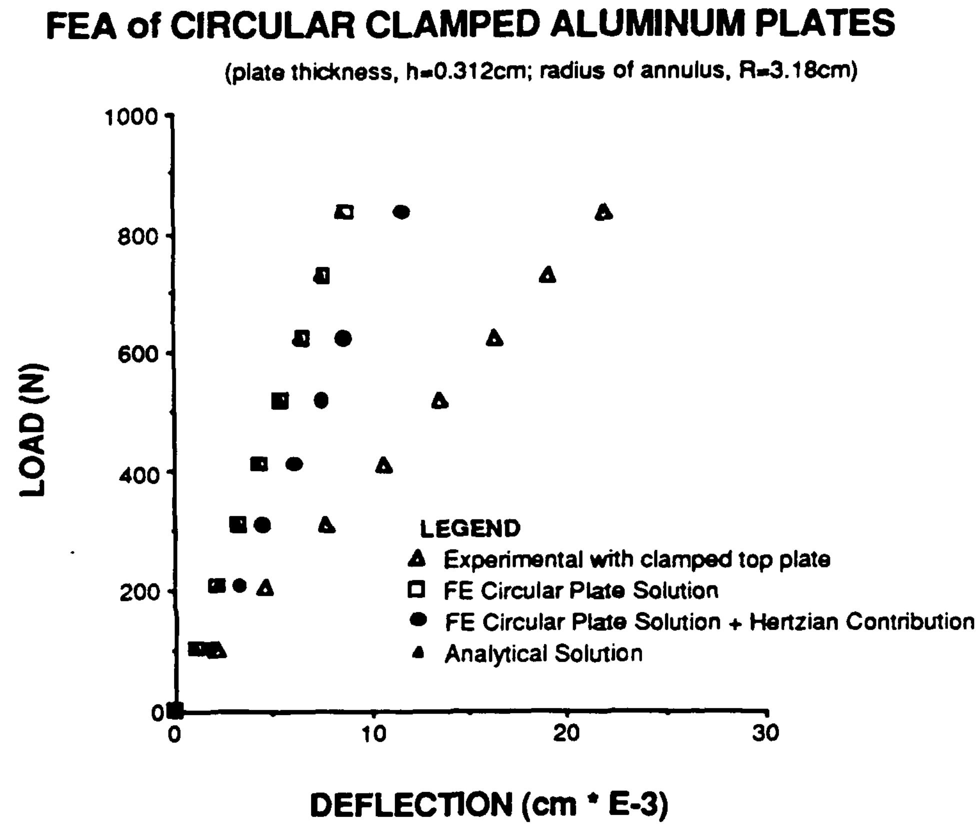

Figure 4.11 Analytical and FE solutions to the problem of a circular plate under point load. Static load-deflection experimental results are shown for comparison with the Hertzian contact deformation included. Experimental data points are the average of three tests.

The most likely reason for this difference is that rigid clamped boundary conditions do not exist in the experimental case where clamping is applied with a top plate over the coupon torqued down in only two p'. .es. Other possible reasons could include

contributions from the compliance of the test apparatus and/or the loading tup. Details of the experimental results for the composites investigated are in Chapter 6.

The approach taken at this point was to address these other contributions by modifying the FE models and boundary conditions so that they better represented the physical situation. It was clear, however, that analytical methods would probably be inadequate to accurately predict the load-deflection response in the test apparatus and that more realistic FE models may resolve this problem.

A variety of model modifications was made in order to improve the agreement between the experimental and FEA results. These modifications were based on the author's understanding and observations of the physical behavior of the coupons in the test apparatus. Figure 4.12 shows the results of this analysis. The boundary conditions were changed to reflect pinning at opposing nodes in the vicinity of the clamping pins on the Dynatup test fixture, whereas, the other nodes around the periphery of the annulus opening were modeled as simply supported. In reality, some slipping of the plate off the edges may be occurring. The behavior is, likely, quite complicated and beyond the simple modeling approach suggested here, yet even with this approach correlation between the models and the experimental results is reasonable. As noted by Greszczuk [Zukas 1982] some plastic deformation in aluminum, due to contact deformation, will occur beyond approximately 445 N (100 lbs.). This was observed as local plastic deformation (dimpling) in the test coupons, and could partially account for the divergence of the results in Figure 4.12 since the FE models cannot treat this inelastic behavior.

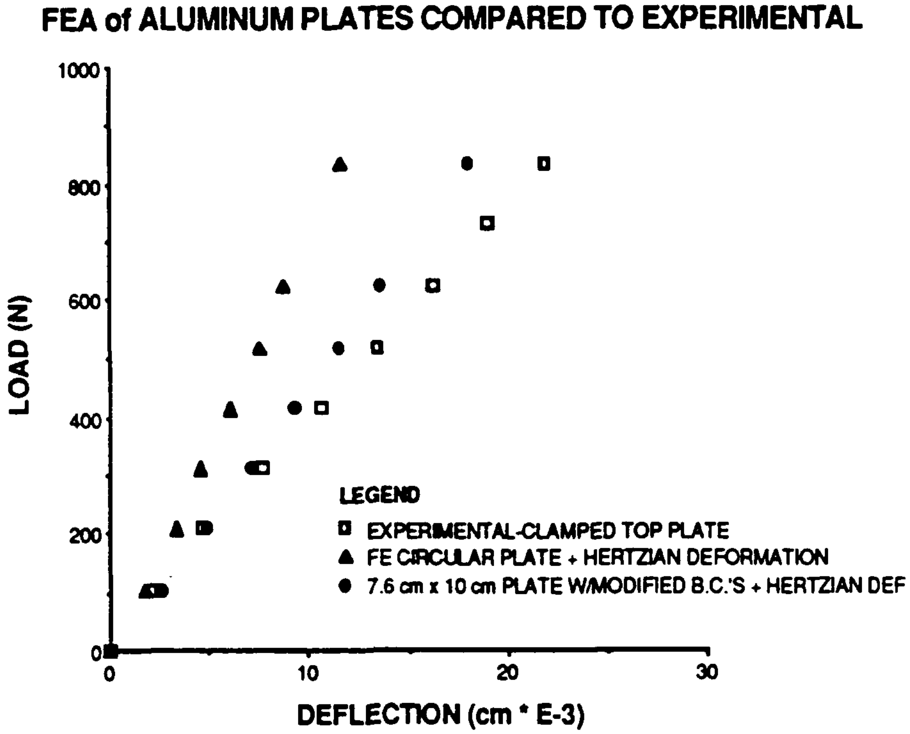

Figure 4.12 FE solutions to various plate models with modified boundary conditions. This modeling was an attempt to more closely represent the additional load-deflection compliance observed in the experimental results. Plate thickness, h=0.312 cm; radius of annulus, R=3.18 cm.

The modified plate, shown in Figure 4.13, models the actual plates used in the experimental phase. As a result of this modeling and analysis of the isotropic aluminum plates, it seemed reasonable to extend this to the composite materials which would be used in the experimental phase of the program: 16 and 32 ply quasi-isotropic carbon/epoxy and carbon/PEEK laminates. Solutions for the 16 ply laminates will be presented; however, as noted by Elber [1983], a thin plate analysis can be used for up to 32 ply systems.

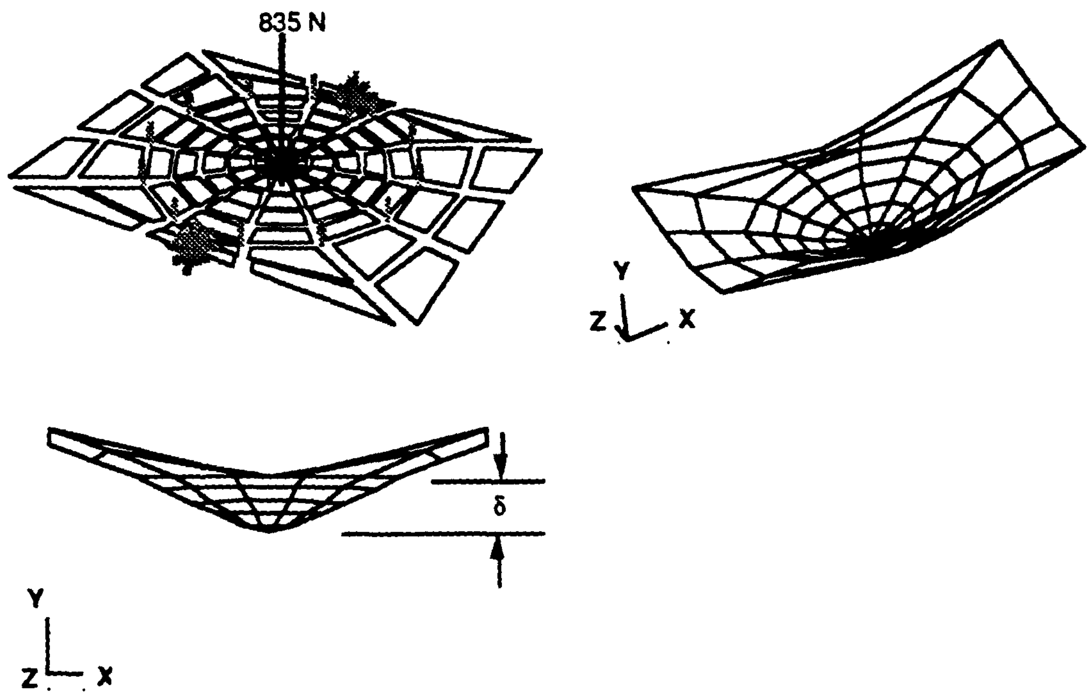

Figure 4.13 FE plate model (deformed and undeformed) of aluminum plate with modified boundary conditions. The plate was 7.62 x 102 cm and 0.312 cm thick. Results of point static load-deflection tests are seen in Figure 4.12.

The preceding discussion suggests that a energy-force balance approach could be used for predicting, *a priori*, low-velocity impact response in real structures where impactor type and kinetic energy, and impact location(s) are given:[1]

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[1] Impactor type, velocity, material properties, and location of impact are determined during the threat analysis in the House of Quality Phase and the structures being evaluated are FE element models of concepts developed during the Pugh concept selection process of the impact design methodology.

1) Use FE analysis to solve the plate bending problem for the structure in the vicinity of the expected impact with known impact energy (this step also captures the structural compliance and its influence on the impact event.)

2) Use an analytical solution to determine the local Hertzian load-deflection contribution.

3) Calculate the load-deflection at this point in the structure, $\delta_T = \delta_I + \delta$.

4) Analyze combined plate bending and contact deformation for the local triaxial stresses and/or strains according to Greszczuk [Zukas 1982].

5) Apply a failure criterion to predict local failure by either plate bending and/or Hertzian contact force.

6) Correlate results with instrumented impact or static load-deflection coupon tests.

For quasi-isotropic coupons and low velocities, the discussion and solutions of Section 4.2.1 apply.

As seen in Section 4.2.2 the problem for determining the load-deflection response for composites can also be decomposed into the plate bending response (with flexural and shear force components, and membrane action) and a Hertzian contact force. The force energy balance for this problem for clamped thin plates is given in equation (16) Greszczuk [Zukas 1982]. For the idealized case of a clamped transversely isotropic thin plate the problem may be solved analytically. The first term in the right hand side of equation (16), the plate bending term, depends on the in-plane properties of

the composite, the Young's modulus, E_r, and Poisson's ratio, υ_r—easily gotten from a laminate analysis program such as GENLAM [Tsai 1988] or CMAP [Gillespie 1987]—the plate radius, R, and plate thickness. It is clear that this term will dominate for very thin plates (depending primarily on the fiber properties), for large plate radii, and for lower in-plane moduli (compliant plates). The second term (the Hertzian term), on the other hand, depends largely on the through-the-thickness properties and may be solved analytically given the knowledge of the impactor and target, as required by equation (9), and the total load generated by the impact at this point in the structure. When moving from the realm of the ideal to the real it is this structural influence not achievable through simple plate analysis which can be determined with FEA; again, suggesting that the approach, Steps 1 through 6 above, may be used to combine these two influences.

For this reason, a FEA of the impact tower and its components was performed to capture their compliances and to help account for their influence of the load-deflection response in the impact test.

4.3 Impact Tower Models and Their Influence on the Load-Deflection Response of Test Coupons

The author has described in Section 4.2 how, under idealized boundary conditions, the stress and strain state due to impact loadings can be developed from an force-energy balance based on the kinetic energy of the impactor. However, in real life rigid boundary conditions do not exist, nor do they in the laboratory. The following general energy expression for an impact event is presented. It may be generally broken into elastic and inelastic contributions.

Kinetic energy of the impactor = 1/2 mv^2 = {Elastic deformations [plate deformation (shear, flexural, and membrane, and contact deformation) + tup and crosshead deformation + deformation of the test fixture + deformation of the impact tower base + deformation of the guide columns + other elastic response in the tower] + crosshead rebound}+ {Inelastic deformations and/or damage [microcracking + delamination + fiber breakage + debonding + plastic deformation of the matrix] + [tower vibration + damping + other structural influences]}. The point is clear; it is difficult, if not impossible, to control and understand each of these.

Clearly, many of these energy absorbing mechanisms are negligible in their contributions. Therefore, it is important in impact testing to identify which are likely to be important to the point of damage initiation in the composite and to understand these explicitly while controlling the others. Those of obvious importance were the elastic plate deformations and contact deformations.

In this study, we have assumed a linear-elastic response up to incipient damage.[1] It is desirable to avoid plastic and non-linear effects which occur after this point because of the complexities in modeling them and, therefore, predicting them. Furthermore, of initial interest to the designer is the point at which damage begins. The major contributors to the linear response are the plate bending and contact deformation response (when local stress exceeds local strength damage occurs); however, the impact

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[1]This assumption seems reasonable given the results in the literature and experimental results shown in Chapter 6. Clearly, the load-deflection plots for the carbon-epoxy systems are linear to incipient damage, as are, generally, the carbon/PEEK plots. The static load-deflection response curves were likewise linear for these systems. Non-linearity-elastic response from membrane effects was not evident.

tower and test fixture are likely to contribute in ways which are worthwhile to understand.

Using the FE software described earlier, a full 3-D model of the Dynatup model 8200 impact test machine was built and analyzed under static loads representing those equivalent to the maximum dynamic loads during the impact testing.

Initially, each component of the test apparatus was modeled and analyzed under a static load to assess its individual compliance. A separate electronic folder for these model files and FEA results was maintained. These compliances were then compared against the idealized plate models with rigid boundary conditions to determine the order of magnitude contribution of each. As expected, the impact tower (described in detail in Chapter 6), as configured and installed at CCM, was very rigid relative to the test coupons. Nevertheless, compliance was clearly identified and quantified. The less rigid and variable components in the apparatus (specimen support fixtures and crosshead) were analyzed in more detail. Three conclusions were clear from these analyses: 1) It is difficult to accurately model a relatively simple structure such as the test fixture, 2) FE modeling clearly shows the importance of understanding and controlling the apparatus variables in an impact test, 3) the installation and setup of the test apparatus and specimen support fixtures should be standardized to preclude variation in results from one test to another. In the following sections the results of the FE analyses for these components are briefly discussed.

4.3.1 "3-D" Tower Models

Figure 4.14 is a close-up of the impact tower model. The model is composed of solid, plate, and beam elements. Material properties are those of the

individual tower components—steel, aluminum, and concrete—as appropriate. The LAPCAD materials template was modified with properties for concrete, wood, and quasi-isotropic properties for selected composite laminates (determined by GENLAM). Component dimensions were based on physical measurements of the tower. Static loads were determined by representative impact tests from maximum dynamic loads measured by the instrumented impact tup.

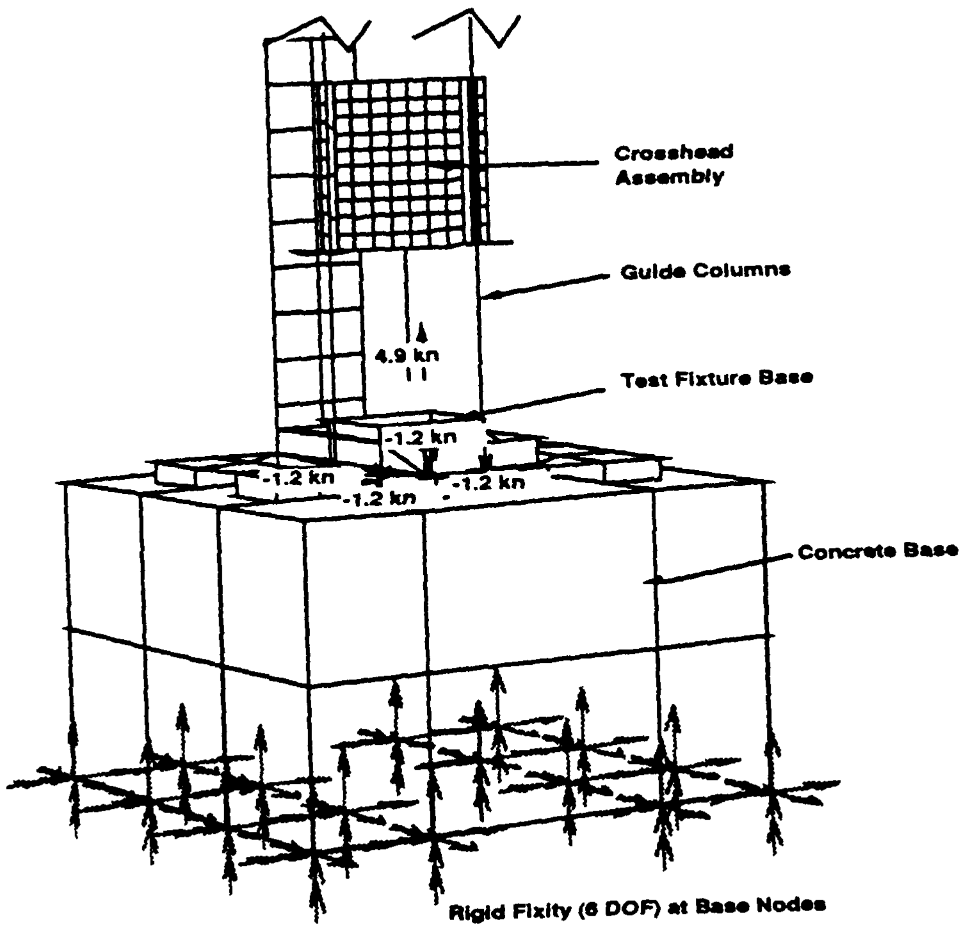

Figure 4.14 Close-up of undeformed wireframe FE model of the Dynatup impact machine on a concrete base. Tower is subjected to a 4.9 kn static load applied to the tup and reaction forces distributed over four nodes in the test fixture base.

The tower displayed exceptionally rigid response, as expected. The greatest compliance was observed in the reaction forces applied to the crosshead assembly, those which actually read the force in the impact tup according to Newton second law (18)

$$m_1 \frac{dv_1}{dt} = -P, m_2 \frac{dv_2}{dt} = -P \tag{18}$$

where the mass and velocity of the impactor and target are represented by the subscripts 1 and 2, respectively. The response is seen in the full 3-D wireframe model in Figure 4.15.

The rigid base demonstrates negligible deformation, i.e., 3 to 4 orders of magnitude less than the expected deformation of a 16 ply composite plate. From these FE results one may conclude that 1) the crosshead assembly must be properly installed to insure accurate impact test results and 2) a rigidly fixed and stiff support base removes compliance in the structure otherwise available for energy absorption and 3) the compliance of the test fixture can be quantified with relatively simple static load-deflection analysis.[1] Node by node and element by element tabular results were obtained for each load case.

The responses of the test fixture base, the crosshead, and guide columns to this load show that the greatest compliance is in the crosshead assembly. The crosshead was singled out for further investigation, the results of which will be presented in Section 4.3.1.

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[1]More detailed study of the test fixture dynamic response may be conducted at this point to determine natural frequency responses of the system.

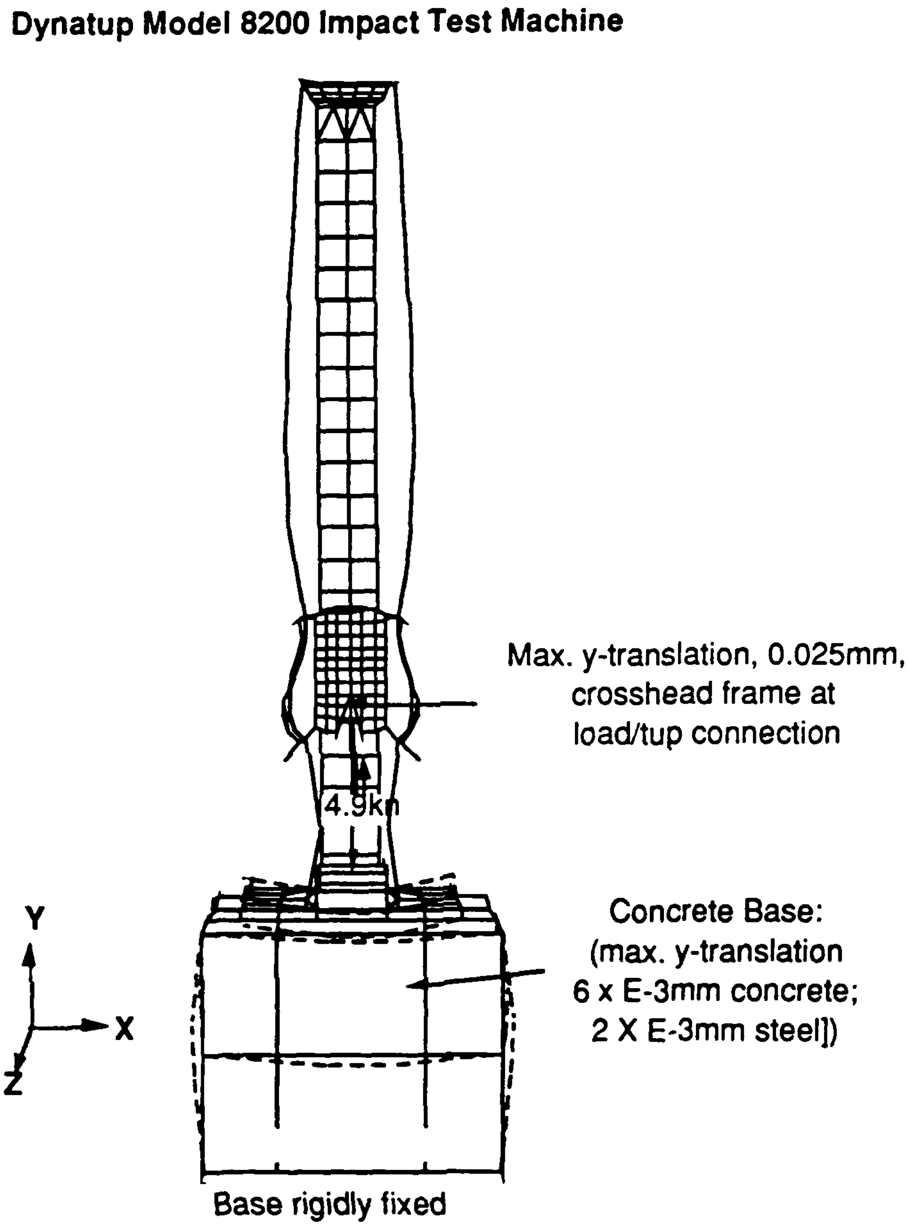


Figure 4.15 Deformed test fixture under 4.9 kn load shows exaggerated deformation response of the crosshead assembly. Closer examination of these effects is presented in Section 4.3.2.

The same tower was modeled with a very compliant base material, E=30 psi., Figure 4.16. This demonstrated, by exaggeration, that the tower installation can influence the load deflection response. Much less easy to model is the influence of bolted connections and joints between system components. Although not a problem with the Dynatup apparatus except in the specimen support fixture, custom impact test machines should avoid these where they could be shown to contribute excessively to system compliance.

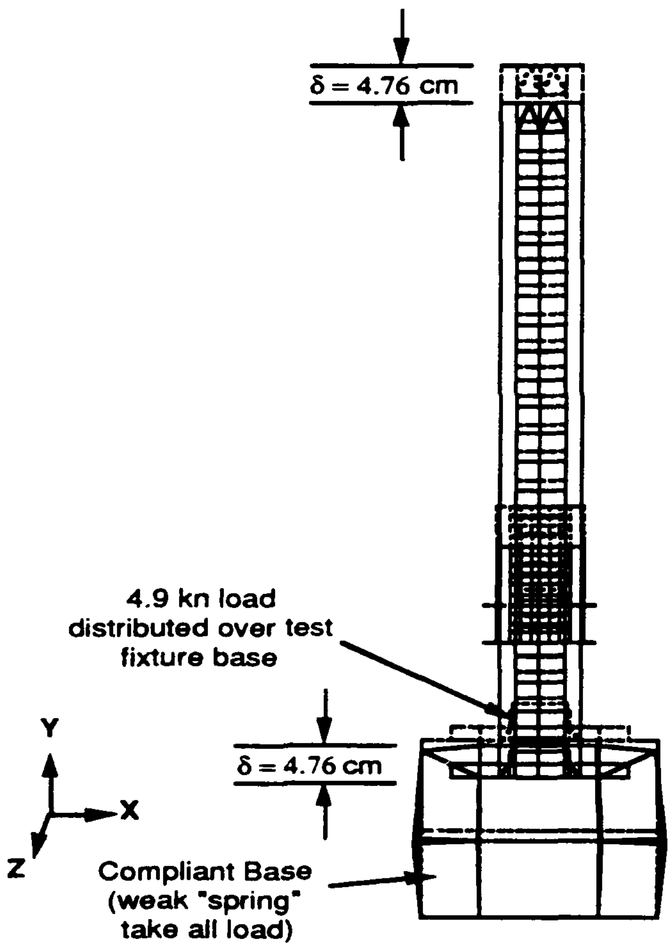


Figure 4.16 Deformed and undeformed Dynatup impact tower with compliant base. All the deflection under 4.9kn load is taken by the base material.

In this case, the weak "spring" ([K] matrix) in the system (the compliant base) provides all the deflection in the load-deflection response. The relatively much stiffer springs in the system (including the test coupon, if it were present) would "feel" none of this load until the weak spring bottoms out, by which time all or most of the impact energy is absorbed, leaving none to damage the specimen. In a much less exaggerated way, real structures and, of course, variations in test apparatus installations provide their own unique contribution to the load-deflection response.

4.3.2 Crosshead Modeling

The individual models of the impact tower crosshead and the combined tower model demonstrated that proper crosshead alignment and configuration were critical to the load-deflection response and necessary to avoid damage to the crosshead or guide columns during testing as a result of excessive bending of the crosshead frame. The crosshead assembly was modeled with a combination of 8 node hexagonal solid elements, 4 node quadrilateral plate elements and tubular beam elements for the tup and guide column sections. Fixity was set at the top of the crosshead assembly where the guide columns extend through the crosshead, and loading was applied at the tip of the tup in the y-direction—through the longitudinal axis of the tup (as in an impact event). Figures 4.17 through 4.19 show three possible configurations of the crosshead assembly: a) without cover plates, b) with cover plates but without the center bottom bolts installed, and c) with cover plates properly installed, i.e., with center bottom bolts installed.

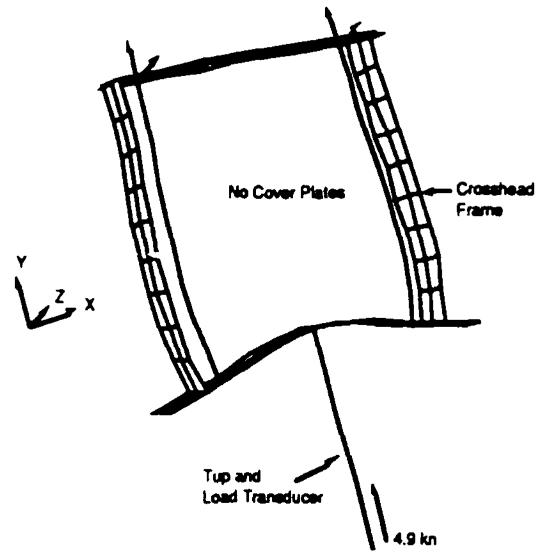
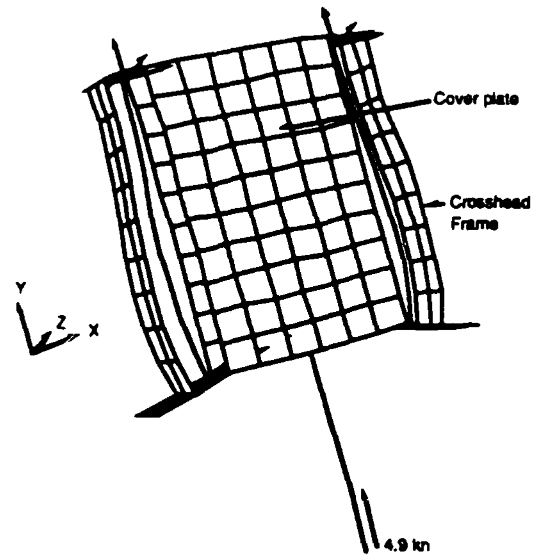


Figure 4.17 Crosshead frame assembly without cover plates subjected to a 4.9 kn load. Maximum deflection is 0.02 mm. Significant deflection occurs laterally in frame side beams which may bind with and bend the guide columns under higher loads.



Fi... re 4.18 Crosshead frame assembly with cover plates but without center bottom bolts installed subjected to a 4.9 kn load. Maximum deflection is 0.003 mm. The cover plates predictably reduce the frame bending.

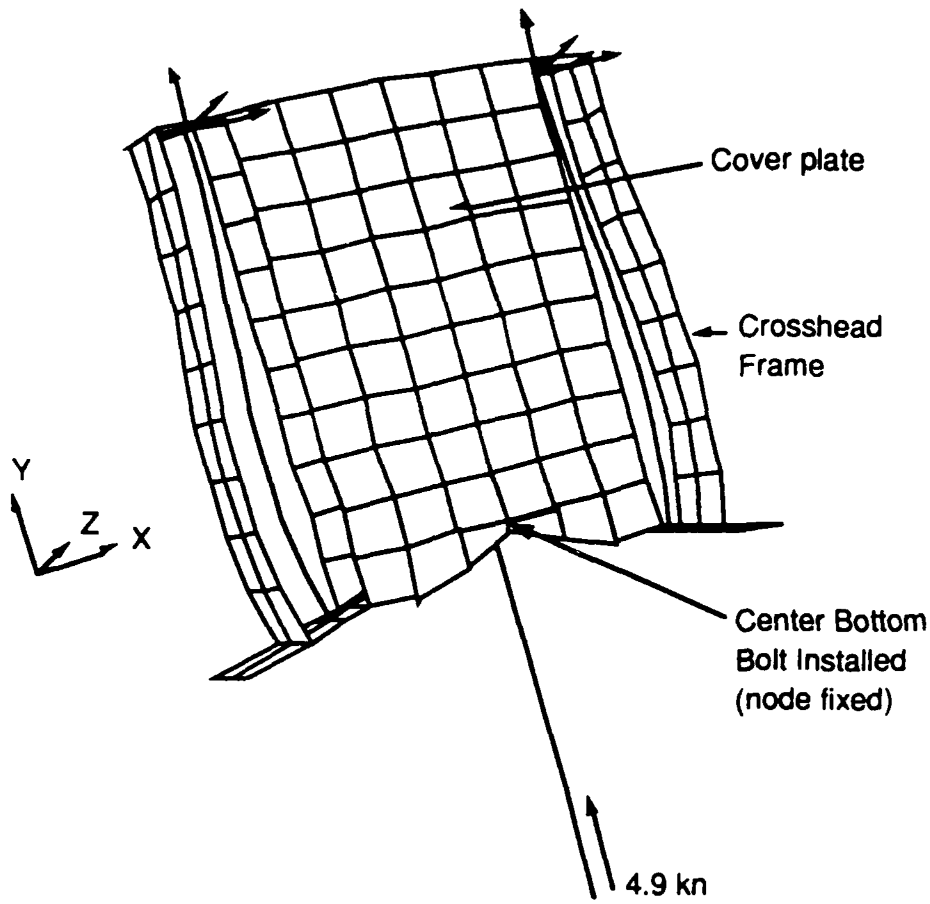


Figure 4.19 Crosshead frame assembly with cover plates and with center bottom bolts installed subjected to a 4.9 kn load. Maximum deflection is 0.002 mm. This configuration provides the stiffest response of all three problems. Frame bending is well below that which is necessary to cause damage to the frame or guide columns.

The accompanying graph, Figure 4.20, shows the influence of these various configurations on the deflection response under a 4.9 kn load applied through the tup centerline. Comparison with modeling results for the crosshead assembly installed in the impact tower show the additional compliance contributions of the tower.

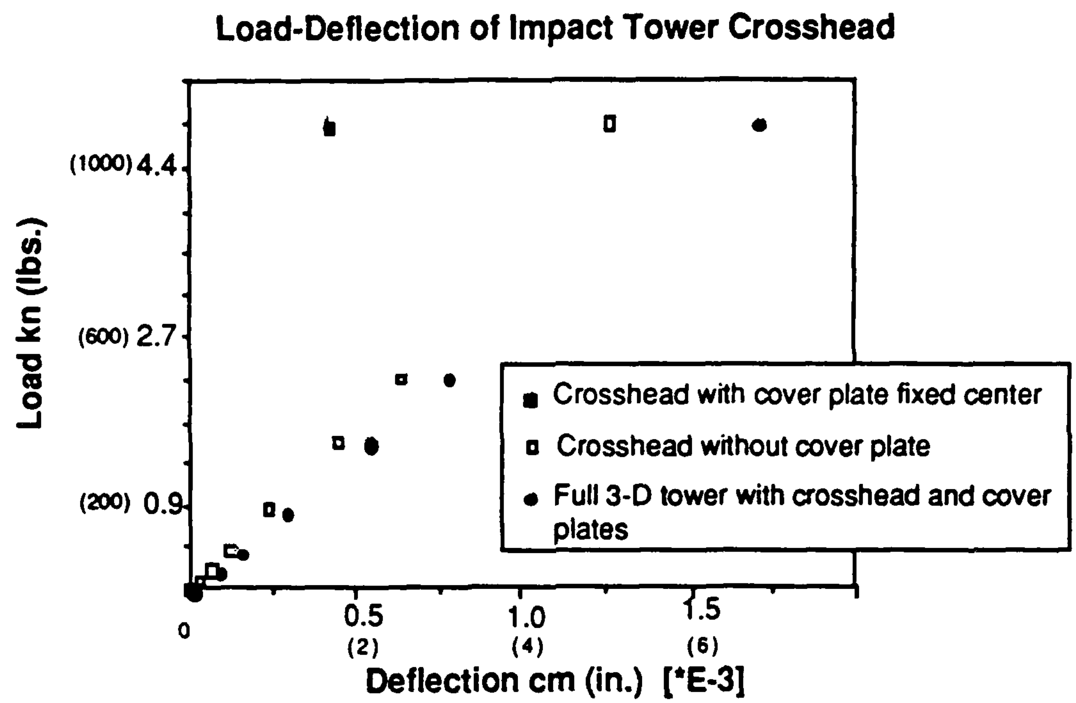


Figure 4.20 Load-deflection response y-translation maximums for various configurations of the impact tower crosshead assembly.

Clearly, without the cover plates properly installed significant bending of the frame can result. Also, in the full 3-D configuration the compliance provided by the additional length of guide columns is apparent.

4.3.4 Specimen Support Fixtures

After the crosshead assembly, the specimen support fixture demonstrated the most variability in the test apparatus compliance. Specimen support fixtures will influence test results depending on their materials, physical configuration, annulus size

and shape, and clamping mechanisms. Typically, idealized boundary conditions may be assumed by designers, but this has been shown in Figure 4.7 to be a poor assumption. Therefore, it is most desirable to model the test coupon response in the test fixture which will be used in the impact test program. Accurately representing the boundary conditions around the clamped annulus presented the most difficulty.

Two common test fixtures were chosen for modeling; the Dynatup fixture and the Boeing support fixture, BSS 7260 [Boeing 1983]. The most obvious differences in these fixtures were their size, materials, opening size and shape, and clamping mechanism. These factors influence the test response. The Dynatup fixture, used in the experimental program, was configured with and without a reduction cylinder which changed the annulus from 5.08 cm to 6.35 cm.[1] A fixture with an annulus of 6.35 cm was used in the model presented.

4.3.3.1 Dynatup Test Fixture

Initially, the Dynatup test fixture was modeled in a 2-D cross section. This was found to inadequately represent the plate bending in the actual fixture, so a full 3-D model was constructed. Figure 4.21 is a diagram of the fixture. The test coupons are sandwiched between the top plate and the fixture coupon platform. The tup impacts the specimen through the center of the top plate normal to its surface.

The greatest difficulty in modeling the combined test fixture and specimen was due to the clamping conditions in the test fixture. The clamped specimen did not respond as either a rigidly clamped or a simply supported boundary condition. As has

been seen in Figure 4.12, modifying the boundary conditions was helpful in improving agreement between real and ideal conditions. Nevertheless, positive control over these boundary conditions during the test is desirable. Other factors relating to the setup and alignment of the fixture prior to testing are addressed in Chapter 6.

Figure 4.22 is a wireframe FE model of the Dynatup fixture with the specimen in place with nodes connected to the annular boundary to reflect real load-deflection response. The fixture is fixed at its base where it would be bolted to the specimen support base.

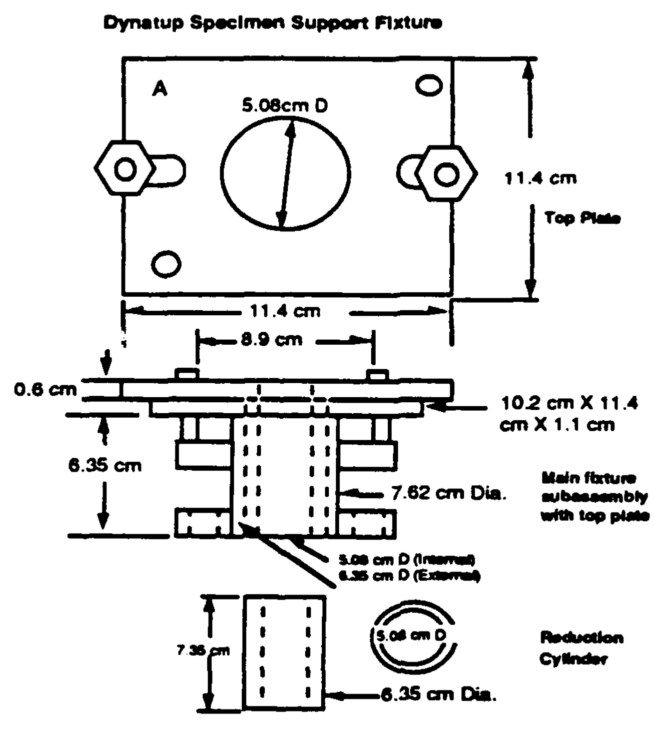
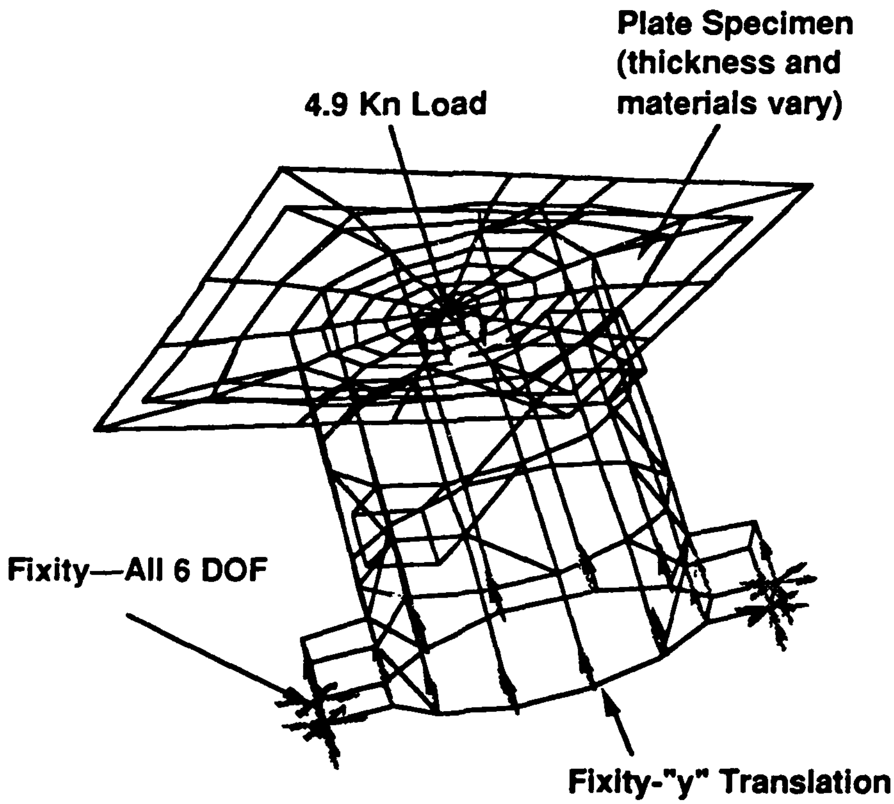


Figure 4.21 Diagram of the Dynatup specimen support fixture. Fixture was modeled with a combination of plates, beam and solid elements based on these dimensions. Material constants for steel—E=30 msi, G=11.5 msi, ν=0.30—were used.

The remainder of the nodes at the base of the cylinder are only fixed in "y" translation, again, reflecting the relatively rigid nature of the substructure. Based on the results of the FEA of the 3-D tower, fixity, as described, is a reasonable assumption when the tower is mounted on a concrete base. A variety of load cases was run to determine the compliance of the test fixture. A deformed model of the fixture from a typical case of point loading at the center of the specimen is shown in Figure 4.23. The load is distributed over the center ring of nodes, 1.27 cm (0.5 in.) diameter.



⁻.gure 4.22 Wireframe FE model of the Dynatup specimen support fixture. A distributed 4.9 kn center load is represented on the model as well as fixity conditions at the base of the model.

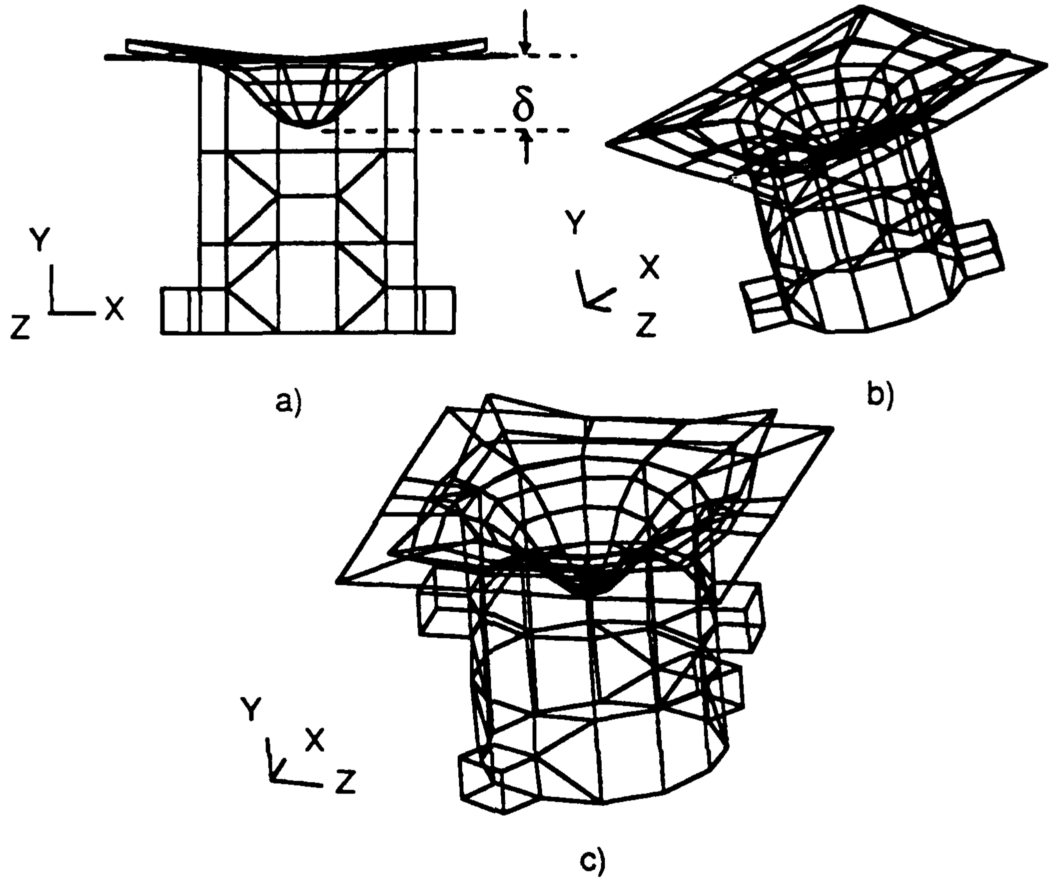


Figure 4.23 Deformed views (exaggerated) FE models of Dynatup specimen support fixture. In the front view, a), the plate bending deformation, δ, of impact coupon is shown. This δ does not take Hertzian indentation into account. Influence of the annular clamping can be seen in the bending of the plate corners of a), b) and c).

As expected the cylinder of the model showed extreme y-translational rigidity; however, there was some radial translation in the barrel of the model, albeit 2 to 3 orders of magnitude less than the y-translation in the plate. The edges of the coupon models also behaved in the manner observed of the real coupons during the static load tests, bending in the positive y-translation as seen in Figure 4.23. Besides triaxial

deflections node by node, maximum, minimum, shear and VonMises stress contours and nodal values are recovered from the FEA. Total deflection in the plate, δ_T, is obtained by summing the deflection results from the FEA with the calculated Hertzian contact indentation, δ_I, using the equations presented in Section 4.2.1.

The influence of the test fixture can be demonstrated by graphing the maximum deflection of the plate against the maximum deflection in the fixture. In the case of these models, that occurred in the circumferential direction on the cylinder body. As noted previously, and as seen in Figure 4.24, this contribution is about 2.5 orders of magnitude less than the plate deflection, itself minimal.

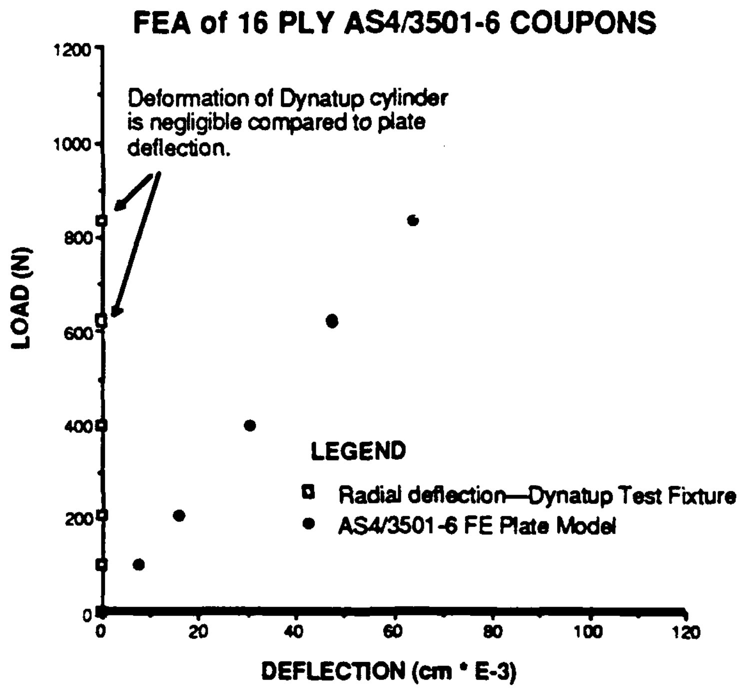


Figure 4.24 FEA load-deflection of 16 ply AS4/3501-6 plate composite plate on Dynatup test fixture. Test fixture has a 6.35 cm diameter annulus Similar results were observed in the APC-2 coupon model. Test fixture influence is obviously negligible with respect to the total system compliance.

Quasi-isotropic material properties, derived from the GENLAM laminate analysis program for lay-ups with stacking sequence [±45/0/90]2s, were inputted to the LAPCAD materials template and used in the plate bending analysis (Table 4).

Table 4 Material Constants for Quasi-Isotropic 16 Ply Laminates [±45/0/90]2s

Material Constants o= in-plane, f=flexural	AS4/3501-6 GPa (msi)	AS4/PEEK (APC-2 GPa (msi)
E_{1o}	54.0 (7.95)	52 (7.52)
E_{2o}	54.0 (7.95)	52 (7.52)
E_{6o}	21.0 (3.10)	20.0 (2.89)
υ_{12o}	0.28	0.30
υ_{21o}	0.28	0.30
E_{1f}	48.7 (7.06)	44.8 (6.49)
E_{2f}	41.1 (5.96)	37.6 (5.45)
υ_{12f}	0.37	0.40
υ_{21f}	0.44	0.48

Figure 4.25 compares the results of the static load-deflection modeling of 16 ply AS4/3501-6 and APC-2 coupons.

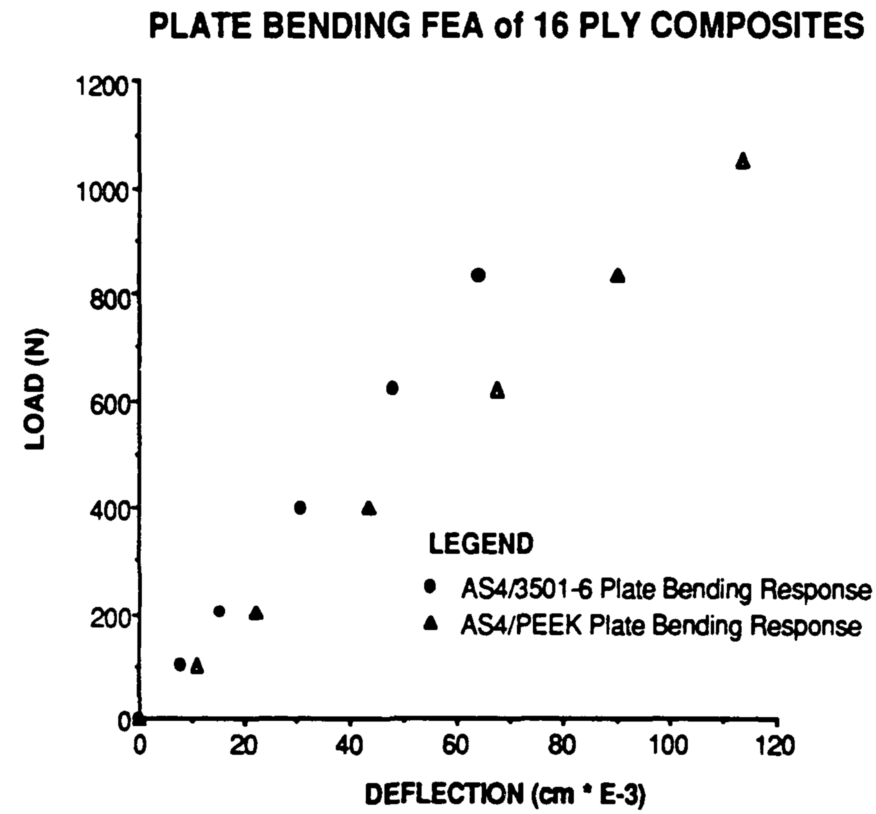


Figure 4.25 FEA static-load deflection results from 16 ply AS4/3501-6 and AS4/PEEK (APC-2) coupons. This comparison shows a stiffer response of the carbon/epoxy coupon. FE model was a Dynatup test fixture with 6.35cm annulus with coupon models of same thickness as experimental coupons.

Hertzian contributions, calculated based on matrix dominated through-the-thickness properties using the equations previously presented, will be shown in Chapter

7 where the results are correlated with the static load-deflection tests and impact tests of the 16 ply carbon/epoxy and carbon/PEEK, Chapter 6.

Obvious responses in the modeling show that 1) the test fixture is very stiff relative to the specimens and, therefore, contributes negligibly to the load-deflection response, 2) the thicker stiffer carbon/epoxy plate deflects less than the carbon/PEEK plate.

4.3.3.2 Boeing BSS 7260 Model

The ease of the graphical modeling interface of LAPCAD and the menu driven dedicated MSC•PAL2 FEA program allow one to quickly model other test fixtures and compare responses in static and dynamic response with each other and with experimental results. Figure 4.26 is a LAPCAD II FE model of the Boeing, BSS 7260, test fixture specified for the Boeing compression after impact (CAI) test. All the elements in the model are solid 3-D elements.

The FE model of the coupon to be tested is placed on the fixture and the nodes are connected, as appropriate, in LAPCAD to reflect the behavior of the specimen. As with the Dynatup test fixture, the Boeing fixture presented problems in achieving appropriate connectivity between the coupon model and the fixture. Nevertheless, load-deflection response of this model can be readily quantified upon achieving reasonable connectivity for a variety of specimen configuration, and clamping and loading conditions. A detailed study of these influences on this fixture was not conducted due to time constraints. However, those cases which were run suggest that the fixture will influence the dominant plate loading and Hertzian indentation contributions.

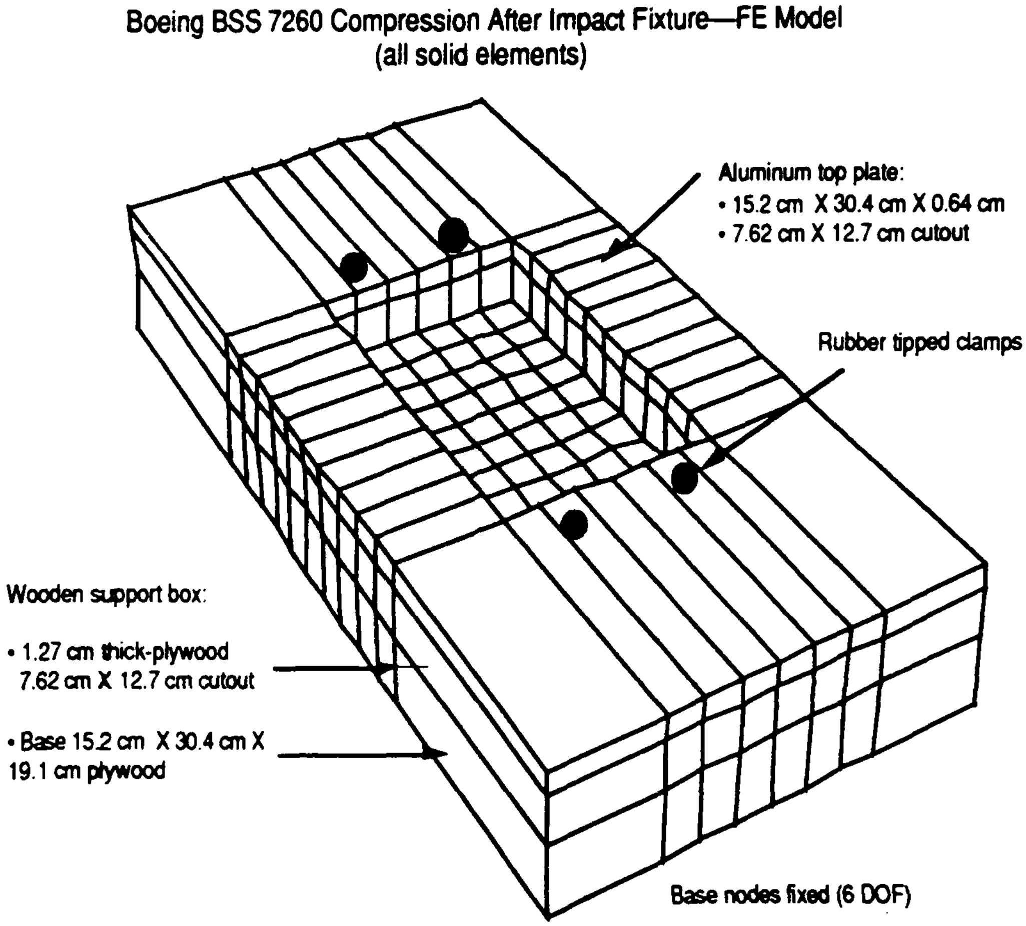


Figure 4.26 FE model of Boeing, BSS 7260 compression after impact test (CAI).

4.4 Summary and Conclusions

A FE algorithm for the impact design methodology has been described which may be used to evaluate material and structural concepts developed in the Pugh concept selection process. A discussion of FE element modeling and analysis tools for conducting analysis to gain structural insight into impact response of structures has also been presented. The approach for this analysis is based on treating low-velocity impact events in a quasi-static manner up to the point of incipient damage. The influence of a standard impact test machine on the impact testing of composite plates has been demonstrated and a method by which a combination of numerical FEA (to account for plate bending effects) and analysis (for determining the Hertzian contribution) has been described. This approach would be used in a "cut and paste" manner, treating the impact tower as a structural surrogate, isolating its influence on the impact response, and then comparing that influence with the FE models of the concept structure.

The significance of $\varepsilon_{90°}$ was noted for providing a first order estimate of impact damage if one assumes transverse tensile cracking as the initial failure mode. In cases where this assumption holds, i.e., impactor velocities less than ~10 m/sec [Cairns 1987], impact energies less than 41 Joules [Moon 1988], and plate bending predominates only static load tests/data, eg., 90° flexure test, would be required. The "cut and paste" approach described in this chapter would provide the next level of design-decision support data.

The experimental results of Chapter 6 will be correlated in Chapter 7 with the modeling results presented here to verify the validity of these assumptions.

CHAPTER 5

TEST AND EXPERIMENT DESIGN FOR IMPACT RESISTANCE

A good plan today is better than a great plan tomorrow.

Dwight D. Eisenhower

5.1 The Role of Experiment Design in Impact Testing

It seems there are nearly as many impact test methods as there are variables to test and responses to measure. Clearly, one of the major challenges to the designer is sorting through the myriad possibilities which exist in this regard, and selecting methods which have meaning in his/her design problem. Compounding the problem for the designer is that there exists no ASTM standard for impact testing of composites [Challenger 1986] and many of those tests which do exist, or which have generally accepted by industry, are either modifications or adaptations of impact tests for isotropic materials—i.e., Izod, Charpy and Gardner impact tests—or develop impact strength measurements based on residual properties under monotonic post impact loads—Boeing, BSS 7260 [Boeing 1983] and NASA/Industry standard [NASA 1985], compression after impact (CAI) tests. These tests have little meaning in terms of real

structural behavior under impact loads, due to problems such as assumptions of linear elastic fracture behavior, scaling, arbitrary boundary conditions, specimen sizes, etc., [Sjoblom 1989]. In fact, as Knott [1983] points out, even isotropic materials suffer from the problems of developing design allowables from these tests, as, for example, in the case of ductile metals very large test specimens may be required to develop fracture toughness, K1c, values due to extremely large plastic zones at the crack tip and the resultant problems of assuming linear elastic fracture behavior. The much more complex fracture behavior in composites, which is clearly non-linear, must preclude these tests from use, in any general sense, for the development of design data.

Nevertheless, some of these tests have utility as materials screening tools or quality control. Others, such as the CAI tests are primarily for determining damage tolerance. Despite being widely accepted and used by industry, they are complicated and expensive tests which produce little information of real value to the designer, and may result in invalid conclusion concerning the "impact strength" of a particular composite [Sjoblom 1989].

Of more general utility, is a test or series of tests and/or analytical methods which capture critical data the designer can use for design-decision support at each structural level in the design—fiber and matrix, to global structural configuration—if one accepts that each level may contribute to the target response and the resultant damage state in the system. The methodology for developing this data was the subject of Chapter 3.

In Chapter 6 we see the results of this TQD analysis of test methods, and impact variables manifested in the generation of incipient damage data for two advanced composite systems using a commercially available instrumented impact test apparatus.

The results of these tests not only provided data for correlation with the models of Chapter 4, but also proved useful in developing a general approach designers may use to optimize these results when combined with common NDE methods and visual examination for laminates and/or small structures.

As noted in Chapter 2, the literature presents a somewhat confusing array of possibilities to the designer for choice of impact tests. The objective of this chapter is to describe the author's use of the TQD tools for developing his rationale for the choices of test method at the laminate and substructural level—instrumented drop weight impact testing—and for the choice of control and response variables for the experimental phase of the research (Chapter 6).[1]

It is the opinion of the author that for real design problems, a TQD application-specific approach must be taken in impact experiment design which complements the concept development, evaluation, and selection process.

5.2 Identifying the "Critical Few" Control and Response Variables for Impact Resistance—A TQD Challenge

As in the case of evaluating different design methodologies, the TQD framework proved useful in evaluating a variety of impact test methods and developing

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[1]While a Box-Behnken "design of experiment" multivariate approach was considered initially in the experiment design, a more conventional experimental approach was chosen for generating the data to support the objectives of the experimental program which included establishing the repeatability of finding the incipient damage point in the laminates being tested. Nevertheless, for more practical design orien ec efforts Saczalski [1989] has shown that a Box-Behnken strategy may provide useful correlations of a variety of dependent impact variables with high confidence and good efficiency.

the critical few impact resistance *control* and *response* variables for low-velocity impact resistance.

5.2.1 The Impact Resistance Customer Wants (CW)

The author's mission relating to the development of impact resistant criteria was to, "Identify the critical few impact test and design criteria for each structural level for inclusion in a global impact design methodology." The customer list was the same as that for the impact design methodology; the most important customer being judged the consortium members. The TQD spreadsheets for this effort are in Appendix E. The short list of the ten most critical customer wants (out of 50 initially identified) for impact design criteria were selected by extensive literature review and by the author's discussions with consortium members and guest lecturers at Center for Composite Materials (CCM) [Abbott 1989, Rogers 1989b, Sun 1989b, Lagace 1990].

The critical few customer wants can be broken down into 1) understanding, controlling and predicting failure mechanisms for durability and damage tolerance and, 2) the development of analytical and experimental tools for identifying and predicting these failure modes. They are listed in Table 5.1 in order of descending rate of importance: (A complete list of customer wants identifying which customers would most likely be interested in them is given in Appendix E.)

Correlations amongst some of these customer wants were easily made and were important to developing the critical few impact resistance quality metrics. Upon completion of the experimental phase, the author was convinced that both the durability of the composite and detection of damage before it reaches critical levels are highly

desirable and may warrant higher rates of importance. In fact, it appears that these two characteristics may be the easiest for the designer to control.

It should not be inferred from this list (or any product of the TQD process for that matter) that this is a "once and for all time" effort. These outputs should be considered as dynamic and will change with one's understanding of problem, the particular application, etc. The feedback loops for handling such changes are identified in the impact design methodology, Chapter 3.

Table 5.1 Top Ten Impact Resistance Customer Wants (CW) and Their Associated Rates of Importance

Customer Wants	Rate of Importance*
1) Delay microcracking	5
2) Superior damage tolerance	5
3) Prevent or control delamination	5
4) Predictable impact performance	5
5) Linear elastic failure criterion	4
6) Superior durability	4
7) Design data development	4
8) Impact damage modeling capability	3
9) Reduce impact damage contribution to life cycle cost	3
10) Ease of damage detectability	3

*CW's are listed in their descending rates of importance.

Clearly, the need to understand and predict impact failure modes was a theme the author heard throughout the two years of this research which related to all ten customer wants! The specific customer wants relating to impact testing and NDE, shown in a complete list in Appendix F, are discussed in Section 5.4. It seemed a reasonable approach to; first, identify the quality metrics at each structural level for determining the appropriate response variables to be measure; second, identify reasonable control variables, eg., mass, velocity, etc. of the impactor, (this would normally be a function of the impact threat analysis in the House of Quality phase); and third, through another TQD process, identify the best test and NDE methods to measure and evaluate these quality metrics.

5.2.2 How to Measure Impact Resistance—the "Critical Few" Quality Metrics (QM)

After the generation of the CW's, the next step was developing the quality metrics (QM) which could measure performance against these CW's.

These QM's were required to be measurable quantities over which the designer has control. The technical difficulty of measuring these QM's was also of concern as it went directly to the issues of reliability, cost, and utility. To reiterate, the intent was to develop, for each structural level, those critical few impact QM's which could be measured in simple and predictive tests, NOT to develop or investigate techniques for improving impact resistance, such as stitching or interleafing, discussed in Chapter 2. (QM's would be used to evaluate the effective of these techniques; therefore, the techniques would, in effect, represent impact design concepts.) The author suggests that this list of QM's could be used as a tailorable baseline for the evaluation of any impact resistant technique or structural concept.

Early in the research it was deemed necessary and desirable to focus on the early stage of the damage development process to avoid having to tackle understanding and modeling of the very complex failure process. While these problems are important to study in order to gain a fundamental understanding of the complete fracture process in composites, it was felt that these models are of little use in practical design problems where the designer is essentially concerned with predicting the incipient damage point and would like to be able to treat the system with a linear elastic failure criterion and with quasi-static assumptions of load-deflection response up to that point. After the incipient damage point has been identified, the designer is interested in residual strengths or, stated another way, the damage tolerance of the system. Current techniques for measuring these residual strengths, as noted, are inadequate for design purposes; therefore, the author focused on the simpler, yet equally important and related issue of durability.

The critical few impact QM's for the constitutive, lamina, and laminate level in composites are shown in Table 5.2. As in the case of the CW's shown in Table 5.1, this list is not intended to be either all inclusive or immutable. As the author's state of knowledge about low-velocity impact and the state technology advance this list can be expected to change. Nevertheless, it probably represents a good starting point for the designer who wishes to evaluate materials and structures for impact resistance. All previous comments concerning feedback to the impact design module based on advances in the state-of-the-art, of course, apply.

Analytical methods and tests for predicting and measuring those critical few QM's at the constitutive level have been discussed in Chapter 2, and the time and place for their consideration in design process has been presented in Chapter 3.

Table 5.2 Critical Few Quality Metrics (QM) Useful in Evaluating Impact Resistant Design Concepts

Constitutive and Lamina Level

1) Lamina critical strain to failure, $\varepsilon_{90°}$

2) Young's, E_m, and Shear, G_m, moduli of matrix

3) Young's modulus, E_f, and tensile strength fiber, σ_{ultf}

4) CTE ratio fiber to matrix, α_f/α_m

5) Matrix strain to failure, ε_{ultm}

6) Fiber strain to failure, ε_f

7) Interfacial shear strength

Laminate Level

8) Damage initiation energy, E_i

9) ε_c-critcal strain ($\varepsilon_{90°}$)

10) Deflection at incipient damage point, δ_i

11) Load to incipient damage, P_i

12) G_{Ic}, Model I strain energy release rate

13) G_{IIc}, Mode II strain energy release rate

14) G_c, mixed mode strain energy release rate

15) Areal damage zone size, A (cm^2)

Table 5.2 (Continued)

16) Volumetric damage zone size, V (cm^3)

17) Visible damage size (impact surface)

18) Damage propagation energy, E_p

19) Effective ply thickness

Structural Level

20) Load to incipient damage, P_i

21) Deflection at incipient damage point, δ_i

22) Damage initiation energy, E_i

23) Location of impact relative to stress concentrators

24) Compliance of substructure (below laminate level)

25) Configuration of stiffeners

26) Distance between stiffeners

27) Bending stiffness of structure

28) Preload of the structure

29) Tensile and compressive residual strengths

In many cases, this data is available from material suppliers and/or the open literature, thus, obviating additional testing; however, from a design viewpoint, an optimum value for any of these metrics can only be given in the context of competing design requirements. For example, while generally one might say that a fiber of moderate modulus and high strength is good for impact resistance, the precise value of this "goodness" is dependent on the particular application and the other design requirements. The systematic recognition of these QM correlations and the ability to optimize the resulting trade-offs of the competing design requirements are strengths of the TQD method.

Of the QM's identified at the laminate and structural levels, the author suggests that identifying the test and NDE methods which provide the easiest, most repeatable, most cost effective solution to evaluate should be chosen. This was the motivation for using a TQD approach for evaluating a variety of test methods, presented in Section 5.4.

Two material systems were chosen to be evaluated by some of these quality metrics, Chapter 6. Those QM's of most interest to the designer focused on the incipient damage point; therefore, a test method which would easily find these data was desired. QM's which were thought to have a high cost/benefit ratio, i.e., too technically difficult for the value of the information gathered, were not evaluated. These included volumetric damage zone, item 16, Table 5.2. Others, while easy to measure, such as deflection at maximum load, δ_{max}, were considered uncritical in a design sense since damage generally occurred at some critical load or deflection below this value or not at all.

Based on the above considerations, the specific quality metrics (representing, for the most part, the response variables in the test design) chosen for evaluation in the test program are presented in Table 5.3.

5.3 Selection of Control Variables

The next step in the test design was to identify control variables which were reasonable for the scope of the study. These control variables can be categorized into those relating to impactor properties and the impact event, and those relating to the material system and structural configuration. In reality, the designer has direct control only over the latter variables; whereas, his predictions about the former are based on probability and experience.

For example, questions might be asked about an impact on a wing surface; what type of wrench will fall (how heavy), from what height (velocity), and at which location? In a particular design problem, the threat analysis for determining these impactor properties would be an important consideration in the test design.

The impactor properties chosen for this study were determined, in part, by the results of the TQD process of evaluating test methods. Since low-velocity impacts, less than 6 m/sec, were believed to be representative of the common "tool drop", drop heights were chosen to assure velocities below this upper bound. In the 5 and 15 Joule impact tests the mass was kept constant, whereas, an additional 2 kg was added to the crosshead to generate 40 Joule impacts.

Table 5.3 Quality Metrics (Response Variables) Chosen for Evaluation in Impact Test Program

Laminate Level	**Metric**
1) Damage initiation energy, E_i	(Joules)
2) Deformation at incipient damage point, δ_i	(mm)
3) Load to incipient damage, P_i	(Newtons)
4) Areal damage zone size	(cm^2)
5) Visible damage size and character (impact surface)	(mm/cm^2)
Structural Level	
1) Load to incipient damage, P_i	(Newtons)
2) Deformation at incipient damage point, δ_i	(mm)
3) Damage initiation energy, E_i	(Joules)
4) Compliance of substructure (below laminate level)	([K])
5) Bending stiffness of structure	([K])

Likewise, impactor mass was selected to represent an upper bound of the typical tool mass, 3.61 kg. (Though this is slightly higher than desired by the author, it was the lowest mass with the available test apparatus, constituting the mass of the crosshead, load transducer, tup [12.7 mm diameter], cover plates, and velocity trip flag.) The tup was made of a non-deformable, high stiffness, tooling steel. The angle of incident impact was normal to the specimen surface for all tests.

The choice of material systems was based on commonly used carbon fiber reinforced plastics, and configurational control variables were limited to changing the size of the annulus in the specimen support fixture between 5.08 cm and 6.35 cm. Other control variables, which are of concern to designer, but which were not specifically addressed in the test program include; environmental conditioning, preload, multiple impact, specific reinforcing techniques, fiber and matrix properties, etc. Details of the test matrix and experimental procedures are addressed in Chapter 6.

5.4 Determining the Test Method and Apparatus—A TQD Approach

Once the control variables and response variables were selected, it was necessary to make a final determination about the test apparatus and support fixtures. The mission for this effort was to, "Develop impact test and evaluation strategy and methods which will allow designers and researchers to predict impact performance in real structures." A complete set of impact testing TQD spreadsheets is provided at Appendix F, demonstrating the development of the qualitative CW's into measurable QM's and then evaluating a variety of test methods against these QM's.

While there was some bias developed on the author's part toward instrumented impact testing as a consequence of the literature search, the use of such an apparatus or the particular type of apparatus was not a foreordained conclusion. The TQD-based evaluation of a variety of impact test methods made this ultimate choice more supportable in terms of its abilities to meet the customer wants for impact testing; however, it also was instructive in identifying the limitations of instrumented drop weight impact testing. Similarly, identification of the applicability and limitations of C-scan NDE, visual examination, and photomicroscopy were highlighted. The details of the test apparatus and setup are discussed in Chapter 6.

5.4.1 Customer Wants (CW) and Quality Metrics (QM) for Impact Testing

The customers for this phase of the study were the same as before; however, their respective importance has changed to favor those generally involved in test design and execution—the design engineer, the laboratory technician, and ASTM. Conversely, the end-product user could be expected to have less direct interest in these methods. The top ten CW's are given in Table 5.4.

The QM's associated with these CW's were broken into two categories, one relating to testing and data acquisition and one to NDE. They were then evaluated and scored against the top CW's using the HOQ technique and automated TQD spreadsheet. Since the value of a particular test method is related as much to the propensity of scientists and engineers to use it, as to the validity or significance of the data generated from it.

Table 5.4 Top Ten Impact Testing Customer Wants (CW) and Their Associated Rates of Importance[1]

Customer Wants	Rate of Importance
1) Simple and predictive impact test	5
2) Understand and predict damage development	5
3) Understand and predict microcracking	5
4) Understand and predict delamination	5
5) Correlate damage to residual strength	4
6) Low cost testing	4
7) Low cost and reliable damage detection	4
8) Reliability of damage assessment	3
9) Easy test data acquisition and reduction	3
10) Ease of damage assessment	3

—witness the widespread use of the Boeing CAI test—QM's relating to these criteria appeared relatively important. Of course, one would hope and should expect that these criteria would correlate in a positive manner. Table 5.5 presents the critical few QM's from the HOQ spreadsheet at Appendix F.

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[1]The connection with analytical and numerical models is obvious in CW's 2, 3, 4, and 5. Appreciating the importance of being able to model the test apparatus and its contribution to the impact event was a direct consequence of these CW's.

Table 5.5 Critical Few Impact Testing QM's for Evaluating Impact Test Methods

Testing QM's	Metric
1) Time to prepare specimens	(time)
2) ASTM standardization	(yes/no)
3) Industries and researchers using the procedure	(integer/%))
4) Data scatter	(std deviation)
5) Test specimens required	(integer)
6) Frequency of test apparatus used	(time)
7) Dimensions of test apparatus (constraints)	(size)
8) Time to acquire test data	(time)
9) Time to prepare test apparatus	(time)
10) Training costs for technicians	(cost)
11) Energy and velocity ranges available	(Joules & m/sec)

The testing QM's were then transferred to a Pugh concept selection spreadsheet for use in evaluating existing impact test procedures. The benchmark chosen was the Dynatup instrumented drop weight impact test apparatus with automated data acquisition, in use at the CCM. This was chosen due to the author's ability to study it first hand and understand its capabilities, its widespread use in research, and its commercial availability. Test methods evaluated against the benchmark included; customized instrumented impact apparatus, Boeing compression-after-impact test, uninstrumented Izod and Charpy tests (ASTM D-256) (These tests may be performed in variety of apparatuses, including drop towers.), and a combination of other Dynatup apparatuses with and without test design strategies.

It may be apparent that the above list of competitors represents a combination of apparatuses, specimen support fixtures, and methods; therefore, difficult to make direct and meaningful comparisons. However, these incongruities, representative of the real problems in the field today, were considered when evaluating the methods in the HOQ spreadsheet, and, as seen in the QM list, allowed evaluation from the point of utility as well as scientific validity. These differences point to one of the challenges to the impact designer, that "impact resistance" or "impact strength," as measured by this variety of methods, has different meaning to different people. For some, a reported CAI value of 45 ksi is meaningful (at least in a narrowly relative sense), whereas, others get meaning from some single value fracture toughness, K1c, measurement derived from a Charpy or Izod test. In composites, however, correlations of these numbers test to test is difficult to establish and their significance to impact response in real structures is clearly meaningless by at least another one or two orders of magnitude.

5.4.2 Evaluation of Impact Test Methods

The final important step in this TQD approach was to evaluate these test methods against the QM's and in terms of their abilities to measure the critical impact resistance response variables, identified in Section 5.2. In accordance with Pugh concept procedures, concepts were evaluated on a simple "+, -, S (same)" scale, relative to the benchmark, for each of the quality metrics. The results are in Appendix F; however, the general conclusion drawn from this exercise was that the use of a commercially available test apparatus, such as the Dynatup series test apparatus, configured for instrumented impact testing with standardized specimen support fixtures and used in conjunction with a test design strategy will provide the most useful design information given realistic programmatic constraints. Positive attributes included: 1) ease of use, 2) relatively small specimen size, 3) wealth of data generated from a single test, 4) repeatability of test results, and 5) simple structure and ease of modeling. Drawbacks of this apparatus were 1) its limitations in testing other than coupons or small components, 2) its inability to test at very high and very low energy impacts, and 3) its difficulty in relating test data to design allowables (a common problem of all impact tests).

In conclusion, regardless of the test method used, a well designed experiment is critical to meeting design objectives and developing design-decision support data. The front-end analysis of the design problem using the TQD approach will help insure that

> 1) Product impact performance requirements, translated to appropriate *response* variables, are identified as quality metrics through the House of Quality process.

2) Impact threats are identified and related to a set of *control* variables for the impactor and the operational environment.

3) Concepts are developed from which additional *control* variables for materials and structures are identified.

These data will then be used to determine the impact test strategy, against real constraints of time, schedule, performance and supportability.

As noted in Chapters 3 and 4, it is apparent from the customer's desire to delay microcracking and the need for a simple cost effective test method that 90° flexure test for $\varepsilon_{90°}$ may provide a good first order estimate of low-velocity impact strength.

The impact test strategy for pure research is more difficult to formulate, since no specific application is central to the effort. As a result, impact testing in this forum typically focuses on developing fundamental understandings of failure modes and mechanisms in a variety of material and/or structural configurations and then attempts to relate the experimental results to numerical or analytical models. Even in this venue, a TQD approach will be useful in focusing on research objectives that are at the same time important to understand and relatively simple to accomplish. Research objectives which meet both of these criteria will certainly find immediate utility to the industrial and academic communities, while limiting the risk to the researcher of successfully achieving those objectives.

5.4.3 NDE—Which Approach?

A complete TQD analysis of NDE methods which would be most useful to the designer was not conducted; however, through the preliminary stages of

investigating NDE methods and finally using ultrasonic C-scan in the work, we realized the importance of using NDE to confirm the load-deflection data generated by instrumented impact testing. For example, it was a fairly straightforward matter to show that transients in the load traces were, in fact, transient and not damage. This was done by examining the C-scans together with the photomicrographs of specimens in which no damage was apparent by the load-time trace. Furthermore, the requirements of NDE to be relatively simple, fast, and reliable were established. The NDE methods used in this study are described in detail in Chapter 6, and, while the robotic ultrasonic C-scan system used was relatively sophisticated, it met all the criteria established above with the possible exception of system cost. A true appreciation and understanding of the impact failure modes cannot be gained without these tools and their concurrent use with other sensorial techniques.

Having defined the test parameters to study, response variables to measure, and a satisfactory test apparatus to support our research objectives outlined in Chapter 1, we were prepared to proceed with the experimental phase of the program presented in the following chapter.

CHAPTER 6

EXPERIMENTAL

The best [test] specimen design is the end-use product.

D.R. Ireland

6.1 Introduction

The overriding objective of the experimental program was to develop information which could support the analysis, through the TQD methodology, of the test methods and impact design criteria which may be of most use to the designer for a first order approximation of predicting when damage might occur in a structure subjected to low-velocity impact. These notions were developed and presented in Chapter 5.

To achieve the above, the following specific objectives were identified:

1) To isolate the test fixture response from the impact event of composite plates, and correlate the load-deflection behavior at damage initiation with quasi-static load-deflection behavior in finite element models of the specimens and test fixture apparatuses.

2) To identify the role of structural configuration and constraint on the low-velocity impact resistance of the tested material systems.

3) To identify the damage initiation energy, load and deflection through low-velocity instrumented impact test for two composite material systems, three energy levels, two specimen support fixture configurations, and two laminate thicknesses.

4) To generate static load-deflection data with the impact drop tower apparatus for comparison and correlation with impact test data of like, 16 ply specimens and with load-deflection response in the finite element models discussed in Chapter 4. (These correlations will be discussed in Chapter 7.)

5) To characterize the impact response and damage states of the two material systems through instrumented impact data, visual and tactile examination, and non-destructive evaluation (NDE) ultrasonic C-scan.

6) To develop data for input to the impact design module.

Decisions on the choice of test apparatuses, materials systems, control variables and response variables to be studied were developed largely through the use of the TQD methodology as presented in Chapter 5, and Appendices E and F. Of course, as is always the case, practical matters of time, materials, and equipment availability were also factors in these choices, but this is realistic and the TQD process helped focus on the critical parameters for this work. The experimental program represents a novel approach to the use of existing and accepted instrumented impact testing on commercially available equipment, NDE methods, and microcomputer-based finite

element analysis to capture the critical low-velocity impact design parameters. The following sections will discuss the materials systems, processing, test apparatuses, and results of the experimental work.

6.2 Material Systems

Standard carbon fiber/epoxy (AS4/3501-6) and carbon/polyetheretherketone (PEEK) (APC-2) materials systems were chosen because they represent CFRPs commonly used in a variety of high-performance applications today. They also provided the opportunity to compare directly (within the test parameters) a thermoplastic and thermoset system of equivalent orientations and stacking sequences. Material details were as follows:

1) Graphite/Polyetheretherketone (PEEK) AS4/PEEK

Trade name: APC-2

Manufacturer: ICI/Fiberite Advanced Materials

P.O.# Sample 7849

Ship Date: 2/8/90

2) Graphite/Epoxy AS4/3501-6

Manufacturer: Hercules, Advanced Materials

Run # 5873-2

Spool #'s 4 & 5

Mfg Date: 17 May 1989

The 16 and 32 ply laminate stacking sequences were quasi-isotropic lay-ups which might be found in high-perfo ...nce applications. (For example, a 16 ply

Graphite/PEEK belly panel was tested on the C-130 cargo aircraft for replacement of the aluminum belly panel, specifically to improve impact resistance against runway debris.)

Three stacking sequences and nominal thicknesses of each material system prepared and tested are shown in Table 6.1.

Table 6.1 Material Stacking Sequence and Nominal Thickness

	Specimen thickness (mm)	
Stacking Sequence	APC-2	AS4/3501-6
16 ply $[\pm45/0/90]_{2s}$	1.9	2.1
32 ply $[\pm45/0/90]_{4s}$	3.9	4.2
48 ply $[(\pm45/0_2)_2\pm45/0/90]_{2s}$	6.0	6.3

The 48 ply systems have equivalent stacking sequences of those reported by Ramkumar [1983] for the F-18 wing skin program and are not intended to be directly compared with the 16 or 32 ply laminates. In fact, in a design sense, it is probably unwise to make general conclusions of the relative merits of one system over the other, based on these or any test results, outside the context of a particular application. Laminate analyses using the Macintosh-based software program, GENLAM® [Tsai 1988], were conducted to obtain stiffness and compliance matrices and in-plane and flexural elastic constants for these systems. As previously noted, these material properties were used in the finite element analysis of the test specimens and support fixtures. In each system, the percentages of 0° plies was well below the 60% rule-of-thumb which promises good impact resistance. Additionally, plies of like orientation were dispersed throughout the laminate and ±45° plies were located at the laminate

surface to improve impact resistance, with predictable loss of flexural stiffness. These issues were discussed in Chapter 2.

In addition to the composite materials, the following isotropic materials were used in static-load deflection tests for correlation with numerical (FEA) and analytical models:

1) Aluminum, 6061-T6—0.123 inch and 0.250 inch thickness

2) Steel,1018 Cold rolled—0.125 inches and 0.250 inches.

6.3 Specimen Preparation and Processing

Composite panels were prepared and processed in accordance with procedures outlined by Carlsson and Pipes [1987]. Fiber volume fractions were determined by the line method and were found to be nominally 63% and 62% for AS4/3501-6 and APC-2, respectively.

The carbon fiber/PEEK (APC-2) composite plates (30 cm x 15 cm x thickness [see Table 6.1]) of unidirectional prepreg were stacked, tacked, and then compression molded at 200 psi in the Center's 150 ton Wabash four post, up-acting transfer press. Eighteen plates (three of each thickness) were processed. A slightly cloudy appearance was observed repeatedly on the surface of each plate after processing. By changing the orientation of the mold in the press and the mold top plate, it was determined that this effect was due to some surface irregularity in the mold top plate. The C-scans and instrumented impact results showed no significant variation in results of plates with or without this effect, which may have been due to resin flow to

these regions of lower pressure. Figure 6.1 shows the processing cycle used for the APC-2. After processing, the plates were C-scanned and cut into final specimen size nominally 76 mm (3 in.) wide x 102 mm (4 in.) long x thickness (see Table 6.1) with a diamond coated table saw. A master test matrix was prepared to capture all the pertinent instrumented impact test data and reflected exact specimen dimensions for each test sample, as measured with a precision caliper. The length and width of the specimens were determined by the constraints of the Dynatup specimen support fixture. While specimen thickness was critical in the impact response, minor differences in planar dimensions seemed to have no discernible influence on the impact response. Specimen alignment in the test fixture was carefully performed and top fixture topplate torqued to even clamping force. The length-wise direction was the 0° fiber direction in all coupons.

The test matrix is shown in Appendix G. The material systems were tested in two structural configurations, 6.35 cm and 5.08 cm annulus in specimen support fixture (with and without reduction cylinder), and at three impact energy levels (5, 15, and 40 Joules [3.7, 11.1, and 29.5 ft-lbs.respectively]). It is instructive to note that the 15J level (closer to 16J in the actual tests), which roughly represents a 1 kg (2.2 lbs.) hammer dropped from about shoulder height, 1.52 m (5 ft.), of the average maintenance worker, easily exceeds the energy level necessary to generate significant damage in all but the thickest specimens tested. And, as will be seen later, much lower energy levels were required to initiate damage, as measured at the incipient damage point, in the 16 and 32 ply specimens of AS4/3501-6. In all cases, for the carbon/epoxy coupons, incipient damage energies were well below those required to observe visible damage on the impact surface of the coupons!

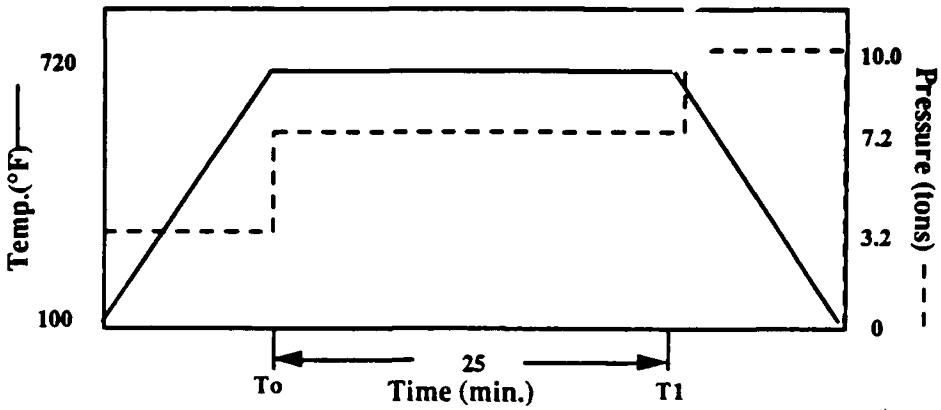


Figure 6.1 Process cycle for carbon/PEEK (APC-2) laminates.

The carbon fiber/epoxy (AS4 /3501-6) plates (30 cm x 30 cm x thickness [see Table 6.1]) were stacked, bagged and processed in the Center's high pressure autoclave according to the manufacturer's recommended processing cycle, Figure 6.2.

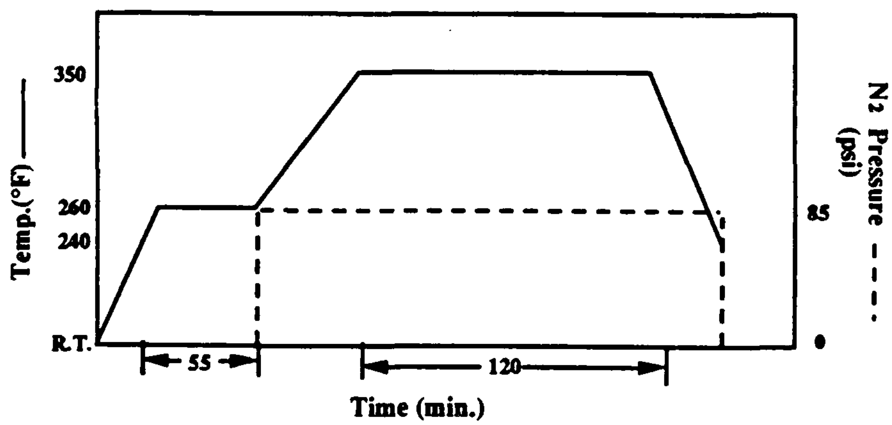


Figure 6.2 Process cycle for carbon/epoxy (AS4/3501-6) laminates.

6.4 The Test Apparatuses

Two experimental setups were used during testing, one for static load-deflection testing and the other for conventional drop-weight instrumented-impact testing. As noted previously, one test objective was to correlate the static-load deflection response with the incipient damage point in the instrumented impact test; therefore, it was desirable to keep the structural configuration and constraints of the two test apparatuses constant to preclude having to make allowances for this in the test results. For this reason, both tests were conducted on the Dynatup Model 8200 Impact Test Machine. A standard Dynatup specimen support fixture with and without reduction cylinder was used in both test setups. The loading tup was steel with rounded blunt tip, 12.7 mm (0.5 in.), in diameter. A detailed physical description of the test tower and support fixture was captured in an Excel spreadsheet for building the finite element models which would be correlated with this test data. A full description of this modeling was given in Chapter 4. A photograph of the test apparatus as configured for instrumented impact testing is shown in Figure 6.3

It is worth reiterating that the test apparatus ana control variable selection, as described in Chapter 5, represent only a handful of the possible combinations of test setups. It is reasonable to expect that these would be determined in part by the particular application as generated in the House of Quality and concept selection phases of the impact design methodology.

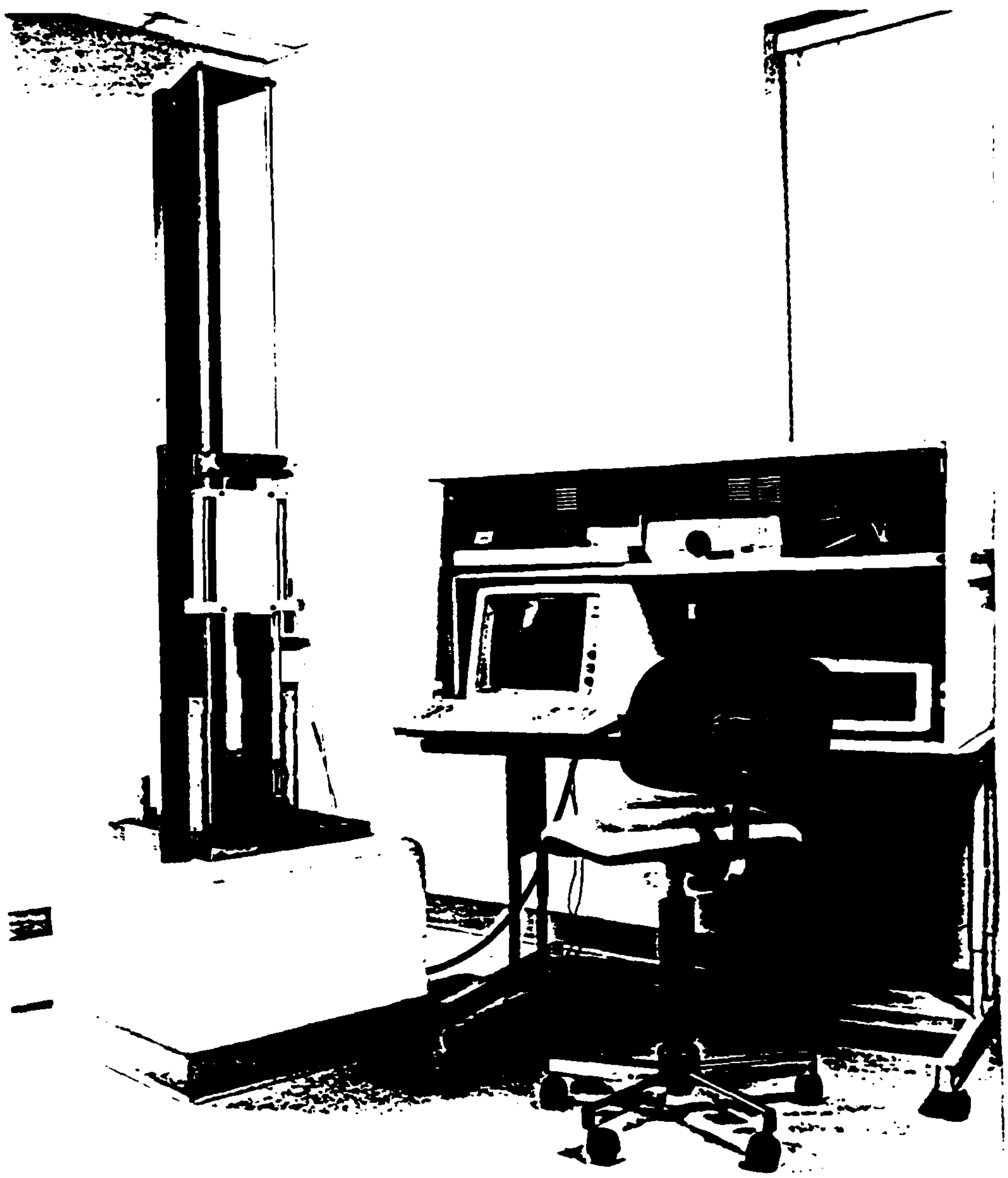


Figure 6.3 Photograph of the GRC, Inc., Dynatup Model 8200 Drop Weight Impact Test Machine configured with Dynatup specimen support fixture and GRC Model 730-I Data Acquisition System. (The system as shown is setup for 5 Joule impact testing. Note the low drop height. Minimum crosshead mass, 3.61 kg, was used for th.. and 15 J impact energy levels.)

6.4.1 Instrumented Impact Test Apparatus and Data Acquisition System

Finite element modeling was used to gain insight into the structural response of the tower during testing. It was evident from this modeling that understanding the compliance of the impact tower was critical. For instance, recalling the discussion in Chapter 4, reaction forces (read by the loading tup) exert bending forces and moments on the tower crosshead, which can influence the test results, particularly at higher impact energies and with stiffer impact specimen response.

For this reason, the installation of the crosshead cover plates was essential to reduce the compliance of the crosshead relative to the impact response of the plate. In fact, the Model 8200 operator's manual for the tower cautions against operating the tower without the cover plates to obviate inaccurate results and possible damage to the crosshead and/or guide columns, although the reasons why these might occur are not stated in the manual! Similarly, alignment of the support fixture in the tower, torquing of all bolts, and mounting the tower on a rigid platform (such as the concrete platform used at CCM) are necessary to preclude unwanted and unseen compliance in the test apparatus which may influence the response of the test specimen. Control of these variables was deemed important to insure repetitive and repeatable response, test to test. Furthermore, any hope that impact test data can be effectively compared from laboratory to laboratory and test apparatus to test apparatus requires that these structural influences be known, described, and accounted for. Ideally, the test apparatus will be 2 to 3 orders of magnitude stiffer than the specimen at the point of loading so that its influence may be neglected. Figure 6.4 is a diagram of the test fixture, identifying the critical components.

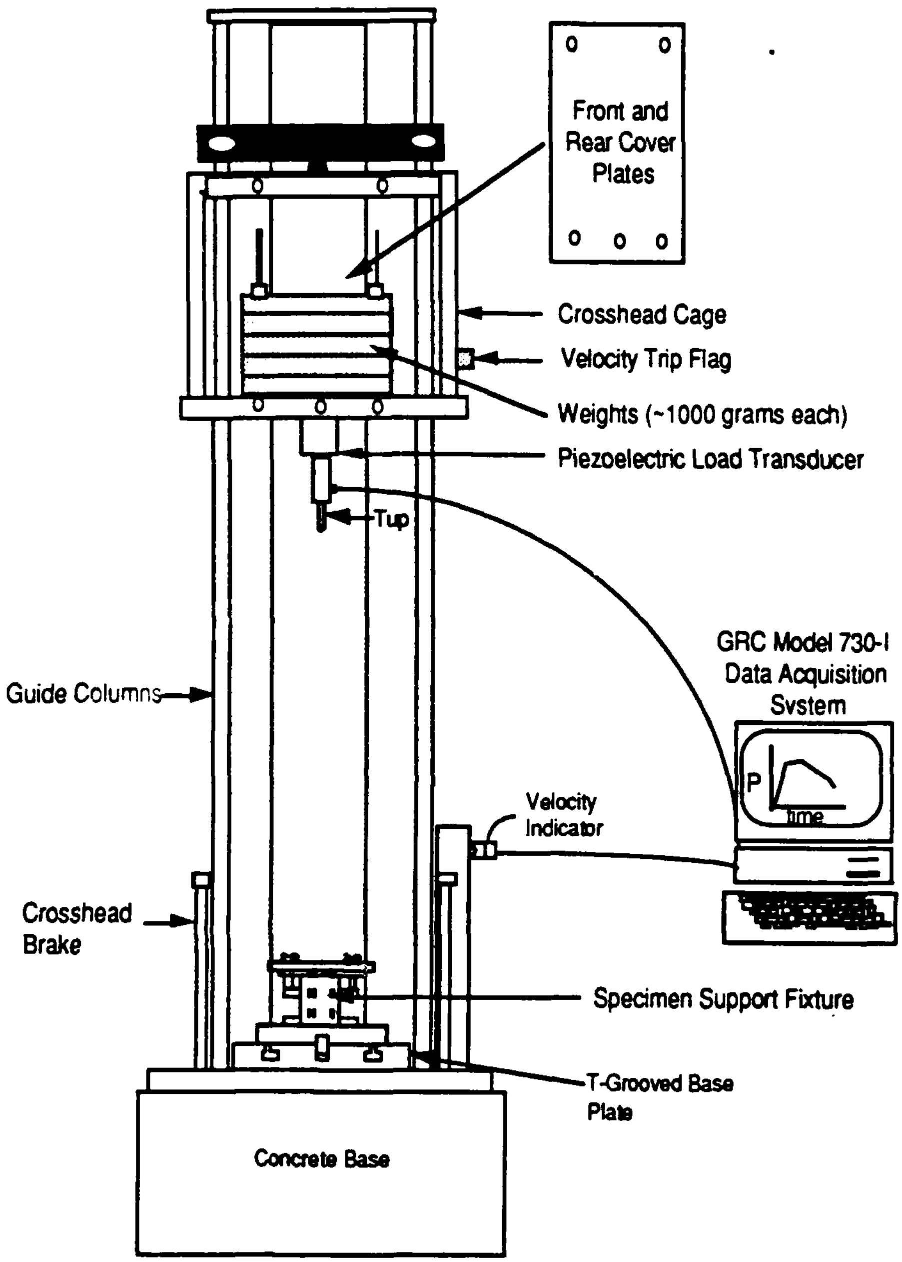


Figure 6.4 Diagram of impact tower showing the critical structural components. (Details of their influence are addressed in Chapter 4.)

While the comparative response of the two material systems being tested was of some interest and produced some interesting, if not surprising, results the primary objective of the instrumented impact testing was to identify with confidence the incipient damage point in the load-deflection (time) response of the impact test for comparison with the static load-deflection response and the models. To do this it was essential to have accurate values for the test input parameters. Of these the crosshead mass, incident impact velocity, and tup sensitivity were most critical if the plots were expected to accurately reflect the incipient damage point [Lindsay 1990a]. (Prior to our testing program the crosshead, with load transducer, velocity flag bracket and cover plates were removed from the impact tower and weighed on a Mettler PJ6000 digital electronic balance. The impact tup was also removed and precisely weighed.)

The total crosshead mass without extra weights was 3.61 kg.[1] The incident impact energy is given by the following expression for kinetic energy:

$$KE = \frac{1}{2}mv^2 \tag{1}$$

where m is the mass of the crosshead and v is the incident impact velocity.

The velocity was checked with the data acquisition software prior to each testing session to insure that measurements corresponded closely to theoretical prediction; within 1% is acceptable. If the guide columns and crosshead are properly

[1]This is at the higher end of the masses that one might be interested in investigating for tool drop-type damage. However, since tools would typically weigh less than this, a special lightweight crosshead which may be acquired from GRC, Inc. could be used to investigate masses more typical of hand tools.

installed, friction between the columns and guide bushings can be neglected. The following relationship applies:

$$v = \sqrt{2gh} \tag{2}$$

where v is the incident impact velocity, g is the acceleration due to gravity, and h is the height measured from the point of impact to the tip of the tup. (This must be remeasured when specimen thickness changes. Also, the velocity gate must be readjusted.)

The tup sensitivity is an intrinsic property of the tup load cell and is provided by the manufacturer in the specification sheet for the tup. In these tests a 44 kn (10,000 lb.) load cell was used which was well above the maximum loads generated in the 40 Joule tests (approximately 6.5 kn [1500 lbs.]) of the 48 ply specimens; the highest dynamic loads observed. The data acquisition board calibrates the load cell prior to each test based on the tup sensitivity.

The selection of the test fixture specimen support is a critical aspect of the test design, as noted in Chapter 5, and will influence the test results as observed by the finite element modeling results presented for the Dynatup support fixture (used in this work) and the Boeing impact specimen support, BSS 7260, compression after impact fixture. The dimensional constraints of the Dynatup tower in the configuration shown in Figure 6.4 limit testing to coupons or small components; however, larger components may be tested by raising the tower off the concrete base, placing it on a "table" and impacting the part through a hole in the tower base plate. Despite these limitations the influence of changing structural configuration was demonstrated by changing the annulus diameter in the test fixture from 6.35 cm (2.5 in.) to 5.08 cm (2.0 in.).

Reducing the cylinder diameter increases the plate stiffness and changes the plate response, thus, the damage modes, for a given impact energy, material system and stacking sequence. The analogous effect in a real structure would relate to such things as the distance between stiffeners and location of the impact relative to the stiffener or spar.

Equally important to understanding and interpreting the impact response of the coupons are the boundary conditions. This proved to be the most difficult aspect of correlating the response in the static load-deflection and finite element models with the impact tests. As is usually the case, in reality, idealized boundary conditions did not apply, although results from simple plate analysis and FEA with idealized boundary conditions were adequate to test the dimensional validity the models. In observing their response during testing, the specimens, although clamped with a top plate, demonstrated a tendency to elastically deform and/or slip in plane as well as exhibiting the out-of-plane deformation shown by the models. This suggests that test fixtures with more easily modeled boundary conditions might improve the ability to generate predictive data from these tests. These results will be presented in detail in Chapter 7.

The data acquisition system, GRC Model 730-I, uses an IBM/XT PC platform with special data acquisition board. It provides the ability to capture the load history of the impact event over the time range and load range set by the operator (or set to auto scale if desired). The system samples the signal from the piezoelectric load transducer from the moment a change in load signal is identified (at impact) up to the maximum time identified for the test time range. The signal is sampled 1024 times during the test, thus, the resolution of the signal is provided as a function of the time

range specified for the test. The load history of the test is saved to disk by the user and may be recalled at any time subsequent to the test.

Of particular interest in this study was the load-deflection response. The cursor examination plot command in the software allowed relatively easy identification of the large drop in load normally accompanying the incipient damage point. This point was sometimes difficult to identify, particularly for the thicker coupons at low and moderated impact energies. Of these, the thermoplastic coupons presented the most difficulty in picking out this point due to a characteristic gentle yielding behavior. Details of the data acquisition system and software are found in the operator's manual [Dynatup 1990] and the CCM supplement to the impact tower operator's manual [Lindsay 1990b]. Use of the smoothing function was avoided during actual testing and in identifying actual peak loads at the incipient damage load and maximum load; however, this feature did prove useful in identifying the incipient damage point when considerable noise was present in the signal. Ireland [1974] and Cheresh and McMichael [1987] offer additional valuable guidance in the use and interpretation of the instrumented impact tests.

The velocity, energy, time, and deflection were captured for the incipient damage point at maximum load and at failure as well as total time, energy absorbed, and maximum deflection for each test. The impact energy and velocity were also captured and retained in a master test matrix spreadsheet. Of particular interest was the energy at incipient damage. A separate spreadsheet was built to evaluate these data.

6.4.2 Static Load-Deflection Test Apparatus

As noted in the introduction to this chapter, one objective was to generate static load-deflection data for correlation with the incipient damage point in the impact tests; assuming a linear elastic response and quasi-static loading conditions to that point. A number of alternatives to accomplish this was considered; three, using the impact tower and one, using the specimen support fixture setup in an Instron mechanical testing machine with equivalent loading tup. It was judged desirable to avoid any variation in the response variables due to differences in the test apparatus; therefore, an apparatus using the Dynatup model 8200 drop tower was designed. This decision resulted in a practical loading limit in the test fixture of 939 N (211 lbs.), which limited static testing to the thinner (more compliant) 16 ply specimens, and aluminum panels for correlation with FE models. Loading was done incrementally by placing weights in the crosshead cage as shown in Figure 6.5. Readings were taken at each load level. Three replicates of each coupon were tested. A top plate with a 5.08 cm (2.0 inch) annulus clamped each coupon. Coupons were also tested without the top plate for assessing the clamping influence on plate bending. The goal was to measure the deflection of the coupon at the point of loading. Ideally, this measurement would be taken from the back surface of the coupon directly under the loading tup (along a line through the tup center and normal to the coupon surface). Two of the three methods considered (using a precision analog dial indicator gage) would require undesirable modification of the specimen support fixture, or fixture base. Thus, the apparatus shown in Figure 6-5 was chosen.

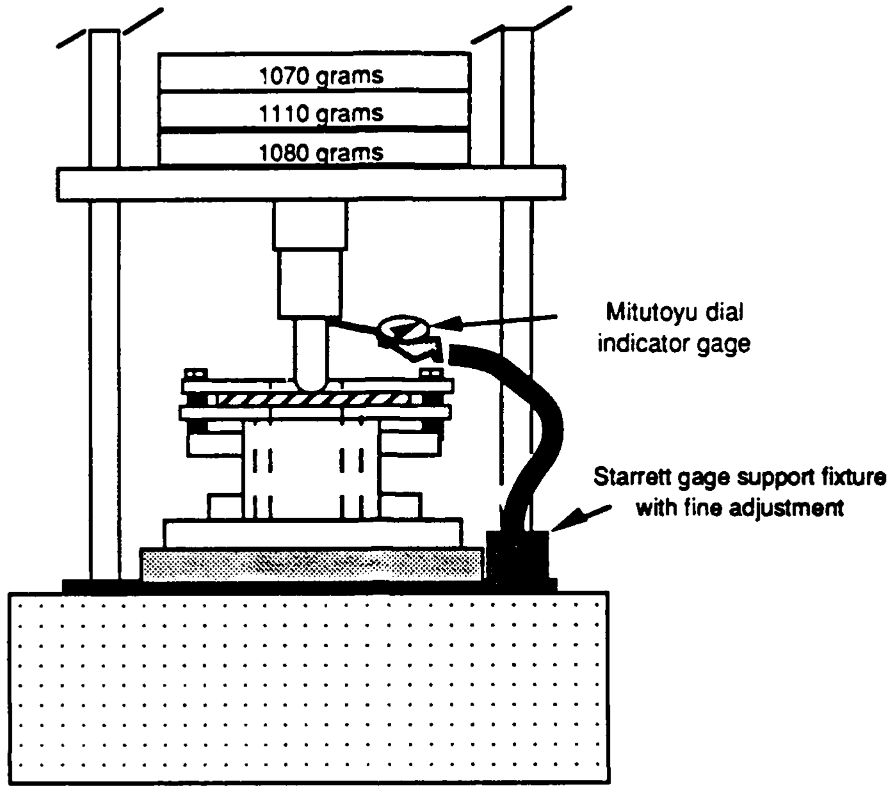


Figure 6.5 Diagram of static-load deflection apparatus in Dynatup Model 8200 Impact Test Machine.

The advantages of this setup were its simplicity, quick setup time, and ease of calibration and testing. No modifications of the test tower or specimen support fixture were required and it was reasonably accurate (0.1 mil error with a maximum gage deflection of 30 mils). The disadvantages of the setup were that 1) it did not measure the plate deflection directly, 2) since loading weights were placed in the crosshead cage, direct loading of the tup was limited by this physical constraint, and 3) it assumed negligible deformation of the tup. On the third point, the deformation of the

tup was evaluated with equivalent loads in a finite element model and, as expected, was shown to be insignificant. The lateral deflection of the dial indicator gage wand was also calculated at maximum deflection and found to be negligible, 0.02% of the total deflection. A photograph of the test apparatus during testing of an aluminum plate is shown in Figure 6.6.

Figure 6.6 Close-up photograph of static load-deflection apparatus.

The impact tests and static load-deflection tests were conducted at standard temperature and pressure with no preconditioning of the coupons and no preloads were applied. A brief discussion of the methods of damage characterization is given in the following sections. These methods were chosen based on their common acceptance to designers and materials scientists, due to their ease of use and ability to provide vital information quickly for use in design-decision support. Sections 6.6 and 6.7, are devoted to a discussion of the impact test results and static-load deflection results respectively. Results of the static load-deflection tests for both the isotropic materials and the quasi-isotropic 16 ply composites will be discussed in terms of the plate theory discussed in Chapter 4. Correlation of these tests is the subject of Chapter 7.

6.5 Characterization of Impact and Static Load Damage

Both impacted and statically loaded coupons were characterized by a variety of means—destructive (photomicrographic) and nondestructive (instrumented impact load-deflection plots, enhanced ultrasonic C-scan, visual, and tactile). It is the data gathered from a combination of these methods which are most useful to the designer in evaluating the materials and structures under consideration from the standpoint of damage initiation, damage development, damage extent, and damage detectability and assessment.

Residual strength properties, although not investigated in this work, are also important, however, only in the context of the loads that the structure may see in service.

6.5.1 Nondestructive Evaluation

Useful information was gathered by a simple visual and tactile examination of the coupons tested. Of interest was whether or not the surface damage could be detected prior to the development of incipient damage in the coupon. This required correlation of these visual data initially with the load-deflection plots and then with the C-scan data to confirm the conclusions. A brief description of the impact and back surface damage of each specimen was included in a remarks section of the master test matrix. Some representative photographs of this surface damage will be shown in Section 6.7 with their corresponding load-deflection plots and C-scans.

Clearly, when external, visual and tactile examinations were correlated with the load-deflection plots and ultrasonic C-scan images, it was evident that incipient damage in all the carbon/epoxy specimens occurred at loads, energies, and deflections well below those necessary to detect them by a cursory visual inspection, which may be common of routine inspections. The thermoplastic coupons demonstrated a much different trend; exhibiting local surface contact deformation from Hertzian contact forces [Zukas 1982] well below the loads necessary to create internal damage in the form of matrix cracking, and delamination. In fact, even in the static loading tests of 16 ply AS4/PEEK visible, albeit barely visible, surface plastic deformation in the contact zone was evident at 939 N (211 lbs.) of load, well below the nominal incipient damage dynamic load level of about 1050 N (236 lbs.). The absence of internal damage in these specimens was confirmed by C-scan and by the load-deflection plots for equivalent dynamic loads. Conversely, for the AS4/3501-6 static tests, a high frequency cracking was heard at ~ 712 N (160 lbs.), although no visible damage was evident when loaded up to 939 N. Furthermore, even though damage was occurring in these coupons it was

not observed in the C-scans. This suggests, at least for the combination of variables investigated in this limited testing program, that impact damage in the AS4/PEEK will be more easily detected prior to reaching critical levels, a matter of concern to designers and end-users.

Also, noteworthy, is that back surface damage in the form of intralaminar fiber splitting and delamination was often evident well before impact surface damage was observed in the carbon/epoxy coupons. Unfortunately, the back surface of these laminates is often hidden from view in real structures or inaccessible to visual inspection. Therefore, the ability to detect the damage at the point of impact prior to critical damage development (perhaps the incipient damage energy, load or deflection) might be a reasonable impact design requirement, such that the visual presence of damage constitutes a repair criterion.

Quantifying the damage in these coupons was done with instrumented impact results and ultrasonic C-scan. The former provided valuable point by point data during the impact event and the latter damage zone size. Clearly, the damage produced in the laminate is a volumetric quantity which can be described, generally, as a frustum of damage; however, measuring this volume of damage, which is in the form of interlaminar delamination, intralaminar microcracking, broken fiber surfaces, fiber debond surfaces, etc., would be a formidable task. Probably, equally useful in a design sense is the planar projection of that damage through the thickness. This was the quantity measured using the Center's robotic ultrasonic C-scan and image analysis system. The system components and interfaces are shown in Figure 6.7.

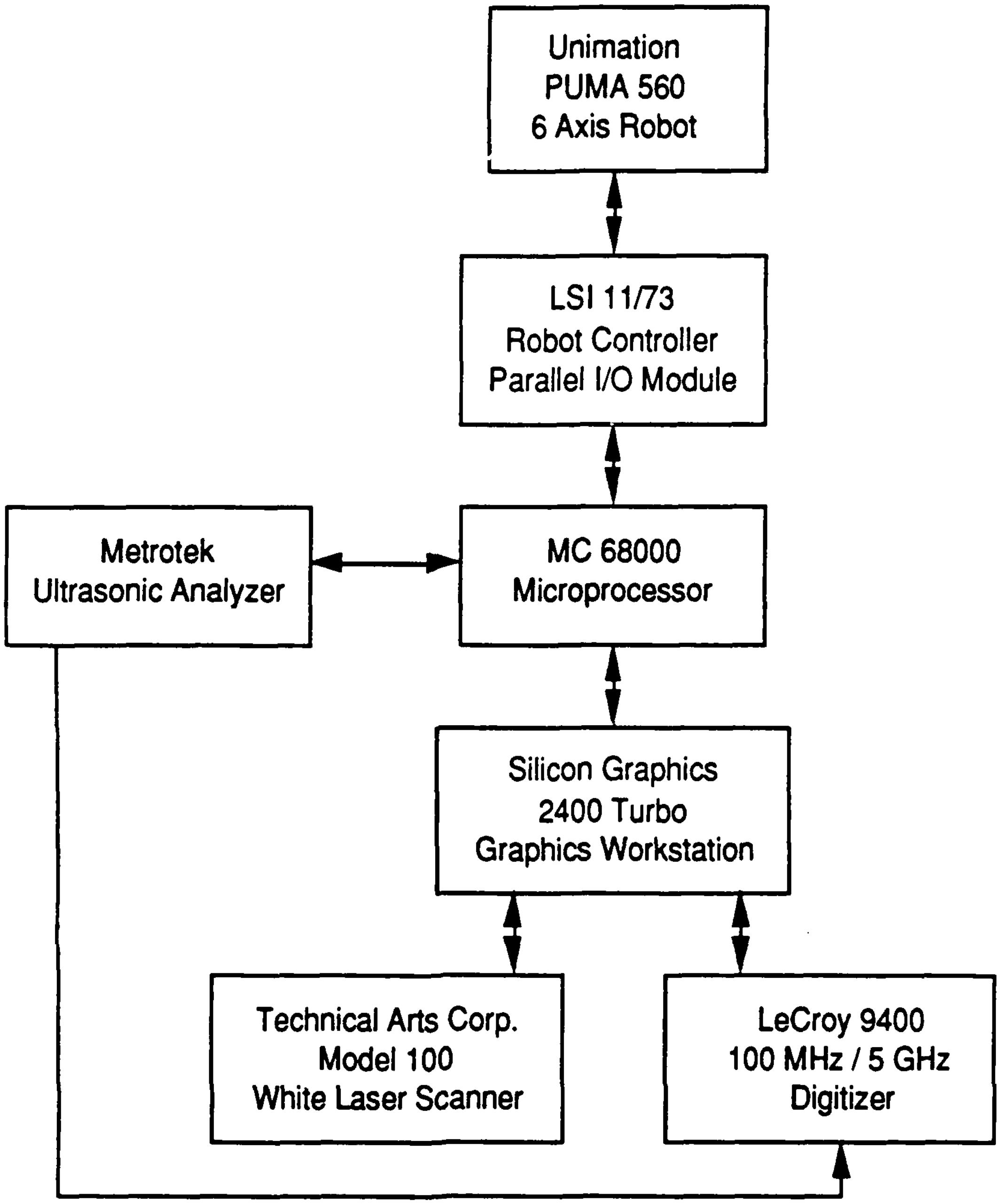


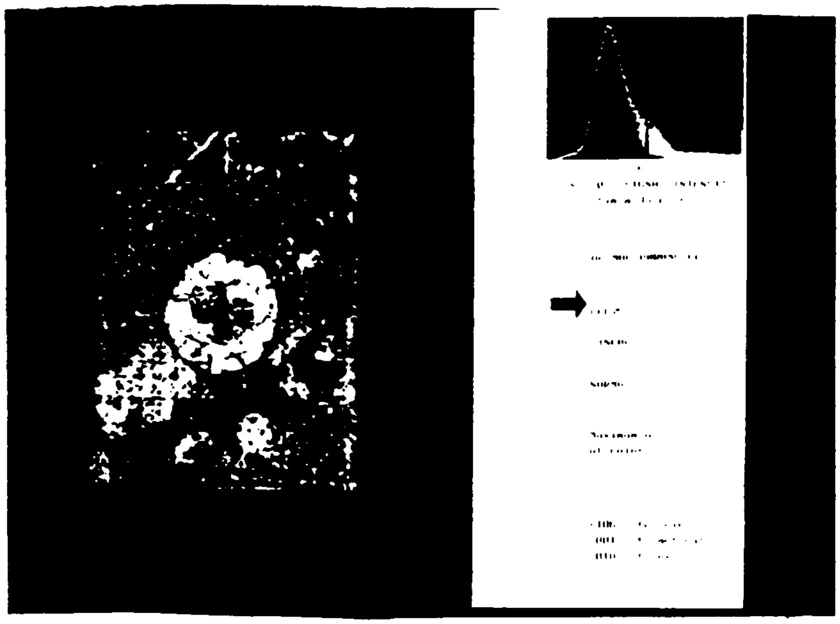
Figure 6.7 Robotic ultrasonic C-scan and image analysis system. (Center for Composite Materials, NDE Laboratory, Robotic C-Scan Instruction Manual)

The procedure used to calculate the C-scan damage area was to 1) C-scan the damaged coupons, 2) save the image file on Silicon Graphics Iris workstation, 3) recall and enhance the scanned image, 4) select and highlight the damage zone, 5) read the dimensions of damage zone (in pixels), and 6) calculate damage zone in cm^2. These data were then loaded into the impact test matrix for correlation with other pertinent data. Results are presented in Appendix H.

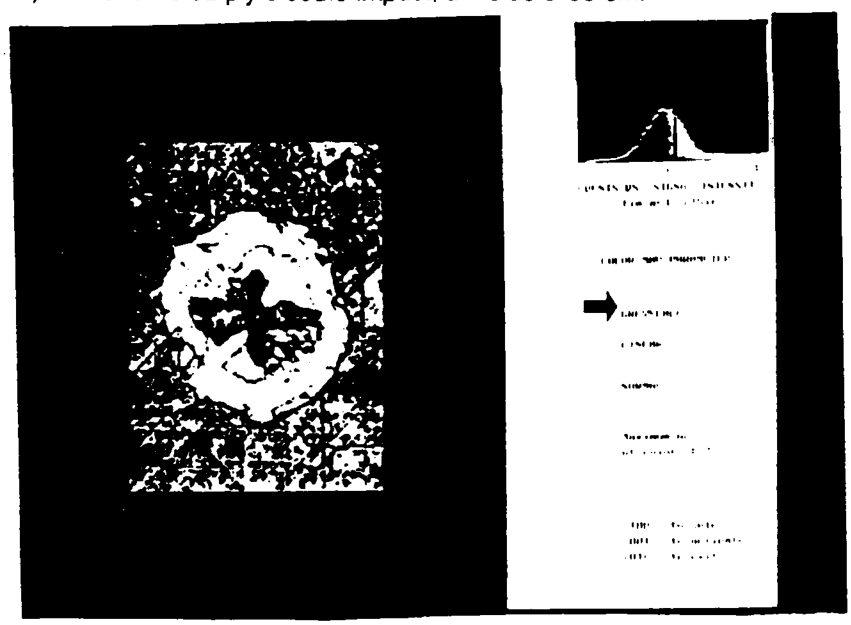
The grayscale photos of the full color scans give some indication of the extensive amount of information, including through-the-thickness frustum shape and delamination development in the coupons. Figure 6.8 a) and b) are representative examples of the quality and resolution of the C-scans possible with this equipment. In Figure 6.8 a) a 32 ply AS4/3501-6 specimen impacted at 5 Joule with annulus of 5.08 cm (reduction cylinder, rc) exhibits characteristic lobe-type delamination formation, described by Cairns [1987] and others [Gosse 1988, 1989].

At the 15 Joule level an equivalent specimen Figure 6.8 b) dramatically exhibits pervasive pie-shaped delamination in a fustrum geometry through the thickness of the laminate. The delaminations run to the annular ring and stop.

Clearly, from these combinations of data, a picture of the unique damage development processes in the thermoset and thermoplastic system emerged. Interestingly, for these lower energy rebound tests, total energy absorbed only slightly favored the thermoplastic composite over the thermoset, suggesting that this metric, as a measure of toughness (durability), may be misleading. Energy, load, and/or deflection to damage initiation, which greatly favored the thermoplastic in these tests, seem to be more reliable and meaningful metrics.



a) AS4/3501-6 32 ply 5 Joule impact, annulus 5.08 cm.



b) AS4/3501-6 32 ply 15 Joule impact, annulus 5.08 cm.

Figure 6.8 Ultrasonic grayscale C-scans of 32 ply AS4/3501-6 impacted at a) 5 Joules and b) 15 Joules.

6.5.2 Destructive Evaluation

Representative samples of impacted coupons were also sectioned through the center of the impact zone, mounted and polished for photomicrographic analysis using a Lietz Vario Orthomat 2 photomicroscope. This technique provided information not readily available using the nondestructive techniques described in the previous section. In particular, the through-the-thickness damage modes can be observed for the two material systems, at different energy levels and varied thicknesses. Again, this data is more valuable to the designer when used in conjunction with the NDE data, instrumented impact data, and sensory examination of the coupons and (by analogy) real structures. Caution must be exercised when examining these photomicrographs because impact fracture surfaces are being altered during the cutting and polishing of the samples; nevertheless, it is instructive to observe the interlaminar delaminations and the intralaminar matrix cracking which have developed.

Because the impact tower has a lower impact energy limit of about 5 joules (3.69 ft-lb), it was not possible to impact the thinner specimens at the damage initiation energy, Ei,[1] and examine the damage; therefore, samples of the statically loaded 16 ply coupons were sectioned and analyzed for evidence of intralaminar transverse tensile and shear microcracking, or other damage which was not evident in the C-scan. This damage was suggested by the audible cracking in the load-deflection test and the corresponding incipient damage load in the impact test. The cracking heard was very high frequency, intermittent, and very short lived—suggesting that it may have been

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[1]The pendulum apparatus designed by Sjoblom [1987] is excellent for the this low-blow type impact test as is the static-indentation test developed by Elber [1983]. These tests, like the simple static load-displacement test, allow one to "creep up" on the incipient damage point initially determined through a higher energy instrumented impact test.

caused by fiber breakage probably occurring on the back surface where tensile strains are highest. The results of the photomicrographic analyses were inconclusive in that damage was minimal, as expected, and difficult to identify. Nevertheless, in the 16 ply AS4/3501-6 specimen statically loaded to 845 N (190 lbs), a few transverse tensile microcracks were observed in the 90° plies away from the mid-plane and one significant transverse shear microcrack and delamination was observed on the back surface (last ply) of the specimen. The extent to which this damage may have been induced during specimen preparation is unknown; however, the damage observed was not inconsistent with observations during the static load test (audible) or with correlations to the incipient damage point at equivalent dynamic loads. No damage was observed in the APC-2 specimens, however, local plastic contact deformation was evident.

The following series of photomicrographs show the through-the-thickness damage in the 16 and 32 ply of the AS4/3501-6 and APC-2 specimen at 5 and 15 J. The failure modes discussed in Chapters 2 and 4 are clearly observed in each of these photomicrographs. These include back surface transverse tensile microcracks, intralaminar shear microcracks, delaminations, fiber breakage. Impact surfaces demonstrate a compressive zone under the tup, tensile cracks at the periphery of the contact zone and the development of shear cracking through-the-thickness in a conical development mode. One observes in Figure 6.9 that the damage in the specimen is minimal. Back surface matrix cracking (transverse tensile and shear) and some plastic deformation at the point of contact is clearly evident. This is attributable to the toughness of the PEEK resin.

Impact Center Line

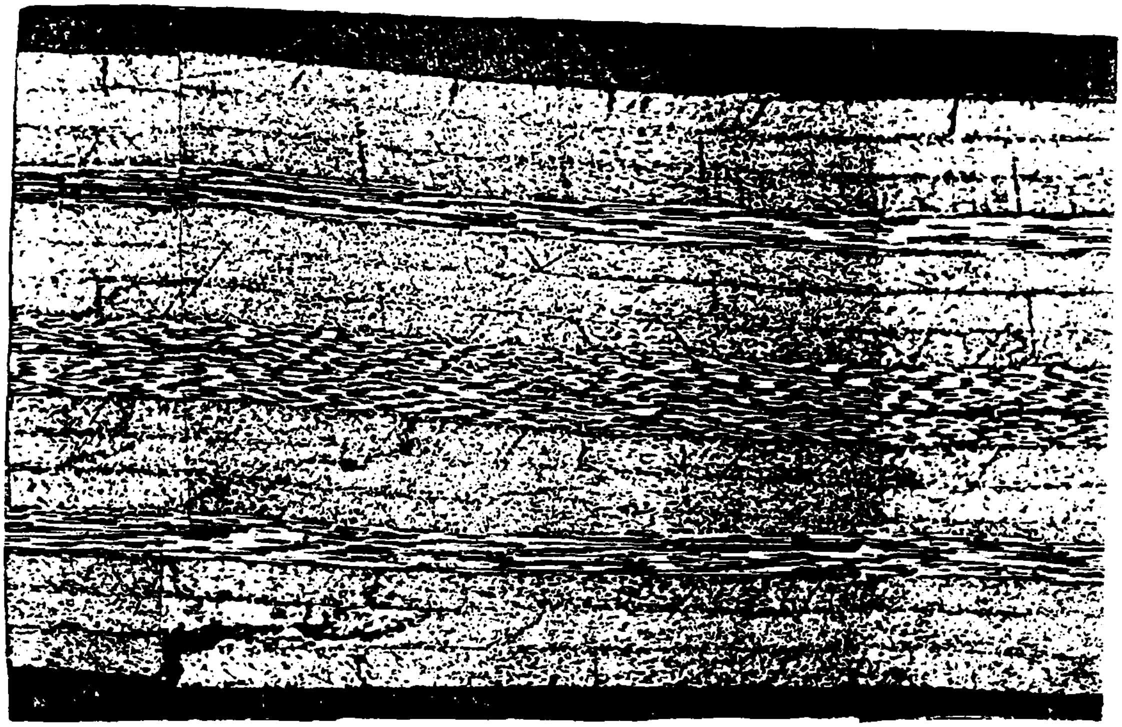


Figure 6.9 Photomicrograph through-the-thickness of APC-2 16 ply $[\pm 45/0/90]_{2s}$ laminate after 5 Joule impact. Magnification (100X).

In Figure 6.10, as noted in the load-deflection and C-scan, damage is much more severe. Matrix cracking and delaminations are pervasive throughout the thickness. Damage results in severe degradation of residual properties; however, little surface damage is visible, compared to the APC-2 specimen, Figure 6.9. The laminate exhibits little damage in a spherical region about the diameter of the tup and up to 5 plies in thickness immediately under the point of impact. Compressive properties dominate in this zone.

Impact Center Line

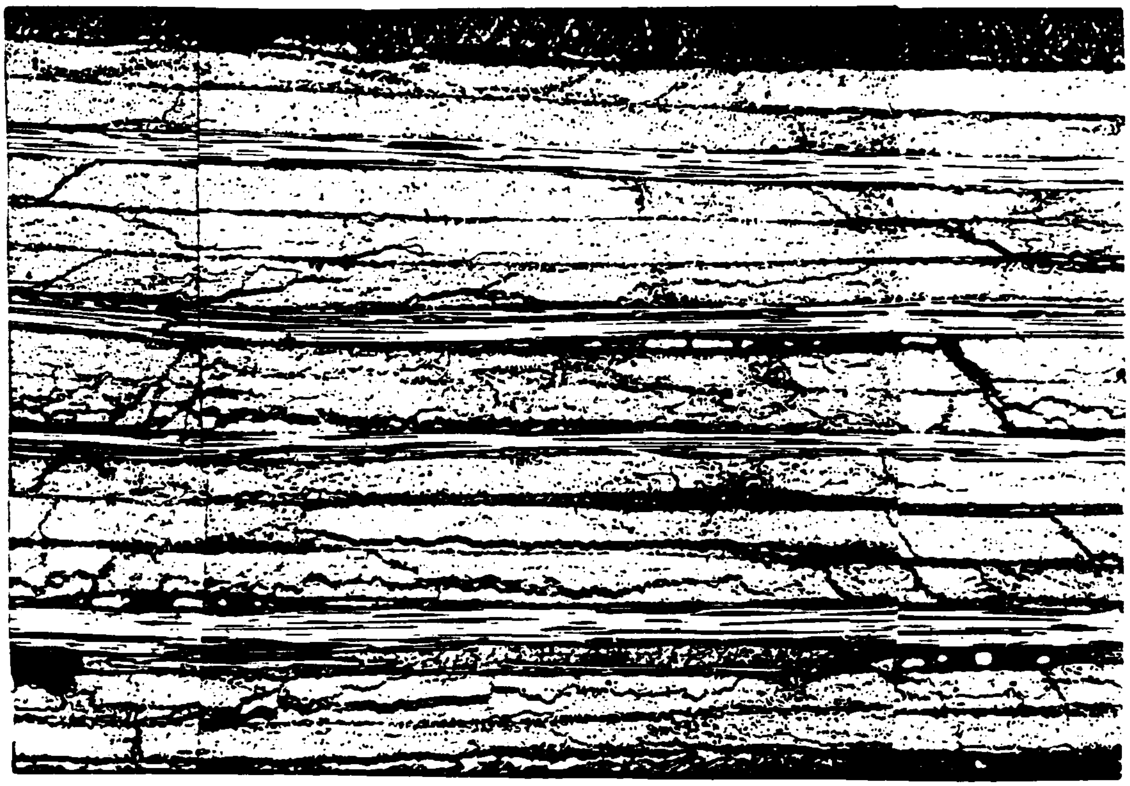


Figure 6.10 Photomicrograph through-the-thickness of AS4/3501-6 16 ply $[\pm45/0/90]_{2S}$ laminate after 5 Joule impact. Magnification (100X).

One observes a similar damage development process in Figure 6.11 as seen in the thinner 16 ply specimen at 5 Joules of impact energy. Transverse tensile matrix microcracks in the plies 30, 31, and 32 offer dramatic evidence of the role the transverse tensile strength or strain plays in the initiation of damage in the laminate. Nevertheless, despite some shear microcracking and delamination, primarily below the mid-plane, the laminate is relatively undamaged in comparison with its carbon/epoxy counterpart.

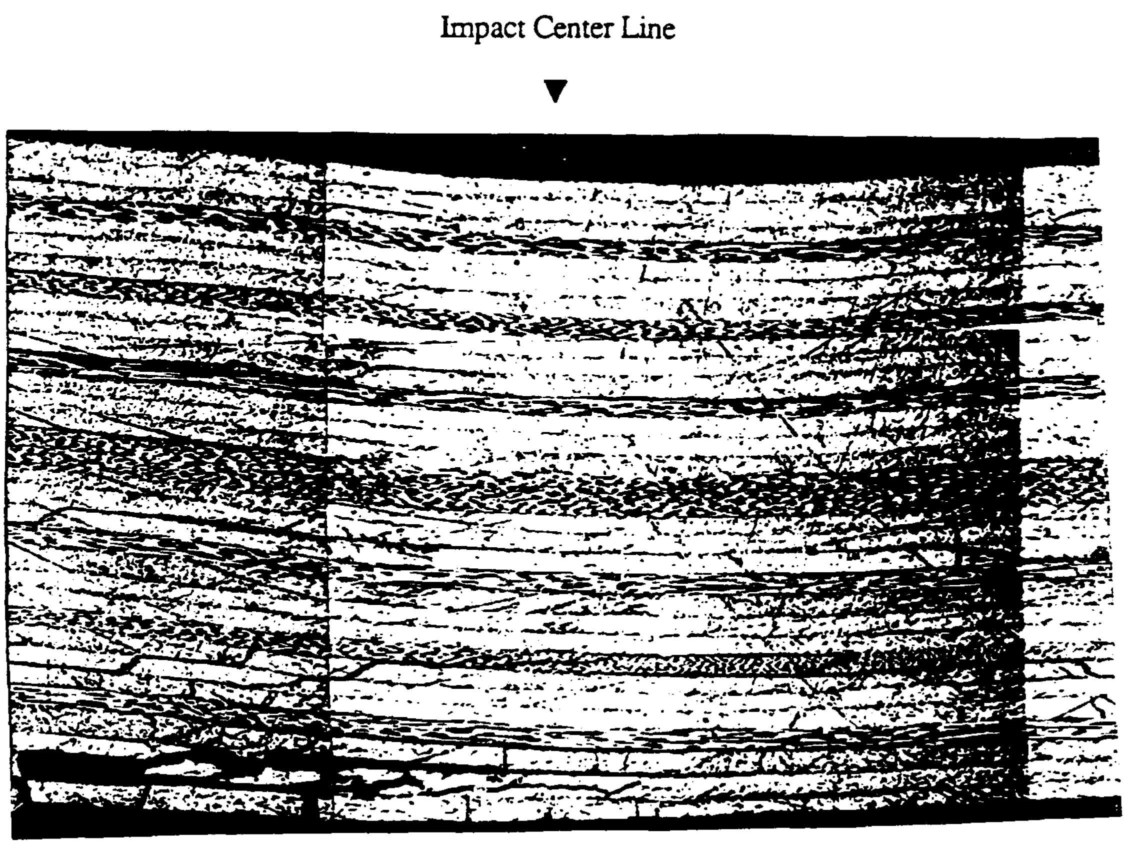


Figure 6.11 Photomicrograph through-the-thickness of APC-2 32 ply $[\pm45/0/90]_{4S}$ laminate after 15 Joule impact. Magnification (50X).

Finally, Figure 6.12 exhibits extensi' e matrix cracking and delamination. In regions of high shear stress near the mid-plane one observes the generation of interply delaminations in the 90° interface plies which are on the order of magnitude of one ply thickness, about 5 mils, and significant back surface tensile cracking and delamination. As with the 5 J-16 ply specimens, the damage is barely visible (BVID) on the impact surface.

Impact Center Line

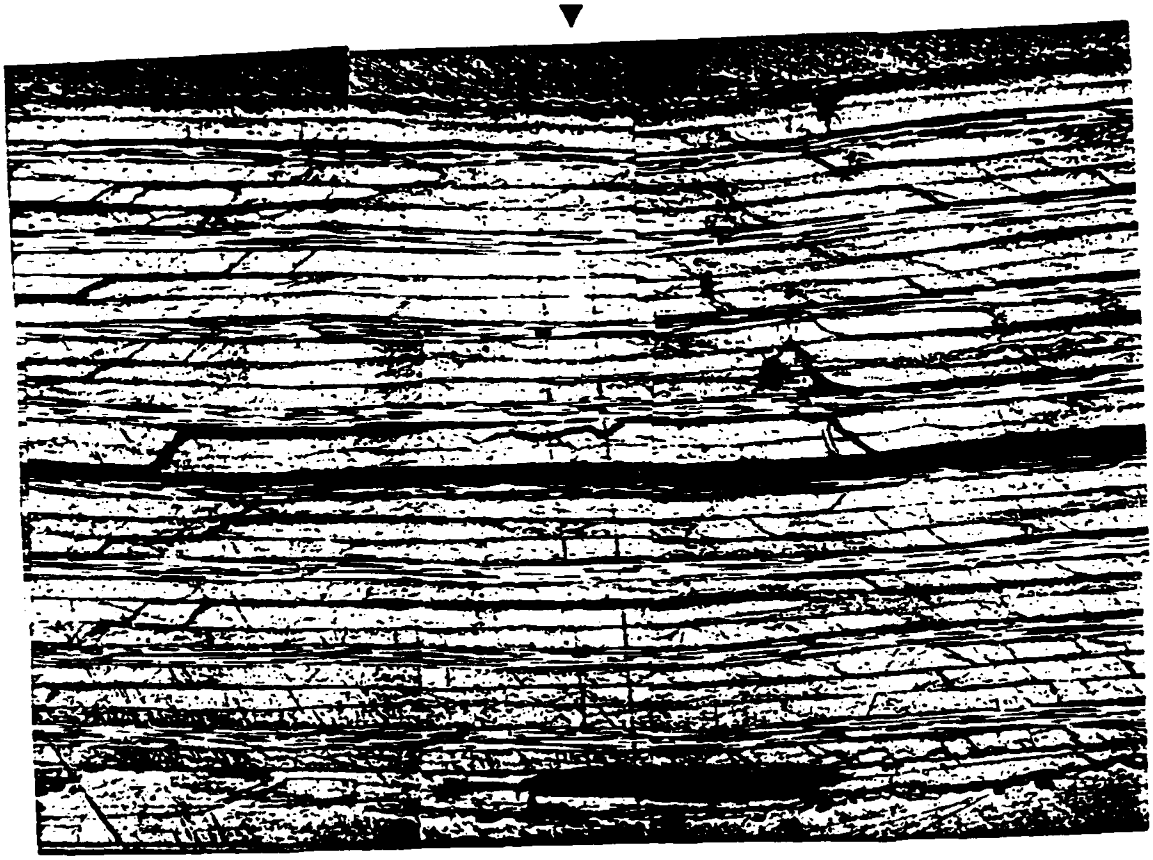


Figure 6.12 Photomicrograph through-the-thickness of AS4/3501-6 32 ply $[\pm45/0/90]_{4S}$ laminate after 15 Joule impact. Magnification (50X).

The statically loaded specimens were also sectioned and examined for evidence of microcracking. As noted previously, the results were, predictably, inconclusive. Microcracking, one back surface transverse tensile crack, and one delamination were observed in the 16 ply AS4/3501-6 specimen. This suggests that the plate bending contribution was dominant and, thus, the incipient damage may be predicted by the in-plane 90° tensile strength or strain to failure.

6.6 Results and Analysis of Load-deflection Plots and Their Correlations with Nondestructive Evaluations

6.6.1 Impact Test Results

The focus of the experimental program was to identify the load-deflection behavior of one carbon/epoxy and one carbon/PEEK system, in particular, to examine each plot for the "point" of damage initiation, or the incipient damage points which were identified in the idealized plots in Chapter 2. This can be instructive in evaluating a variety of materials and/or stacking sequences, orientation, etc., as well as assisting in understanding the global structural contribution when correlated with results of structural compliance in the global modeling scheme. Among the questions the designer must answer are, "Will the damage be visible or easily detectable prior to reaching a critical state (some design allowable for stiffness or strength)?" and, "At what energy, load, or deflection can one expect damage to be initiated for a given set of control variables?" Test Phases 0, I and II, discussed in the Impact Design Methodology, Chapter 3, would most likely be the place where the designer would consider the results of these tests, both in terms of providing data for design-decision support for materials and for particular laminate candidates and/or through-the-thickness reinforcements.

While the graphical results and the scatter of the data are critical to determining design allowables, the complete picture of the test results may be more clear when viewed in the context of individual plots; visual, and tactile examination of the test specimens, ultrasonic C-scan inspection (to determine the extent of internal damage), and (perhaps less importantly) fractographic examination of specimen cross-sections by photomicroscopy and/or scanning electron microscopy (SEM). In our test program all the "critical few" data (as determined by the TQD methodology and reported in Appendix E, TQD Impact Resistance Criteria) were captured in a single test matrix spreadsheet. Additionally, characterization of the impact and back surfaces, based on visual and tactile examination, is provided in the "remarks" section of the spreadsheet.

Through the TQD process it was determined that the inherent durability of the composite structure, in a local context (the area in the immediate vicinity of the impact event), is a function of the incipient damage point which can be characterized by the load, deflection, and/or energy to damage initiation. The point at which this occurs on the load time (deflection) plot is surprisingly easy to identify visually or by use of the "cursor examination plot, <CU>" command in the data acquisition software [Dynatup 1990]; particularly, for the "brittle" epoxy systems (even those with stacking sequences which promote impact resistance, such as those used in this study, i.e., having a high degree of ±45° plies, and dispersion of the plies throughout the laminate). Although, not as evident in the tougher carbon/PEEK systems, the incipient damage point is, nonetheless, clearly identifiable in most instances and only becomes difficult to observe near the system's apparent damage threshold. Furthermore, this material often exhibits a ductile-type behavior, including cratering due to contact deformation and back surface doming, which manifests itself in what appears to be a gentle yielding up the point of more dramatic damage due to matrix cracking, delamination, fiber splitting, and fiber

breakage. In a general sense, the fiber and matrix compete for the dominant damage mode depending on a variety of factors—strain to failure, modulus, strength, interfacial properties, structural configuration, and so on. Of importance and interest to the designer are 1) a generally much higher incipient damage point, typically 30 to 50% greater than the equivalent carbon/epoxy system, and 2) a much lower load to visible damage in the form of impact surface cratering. In fact, as noted previously, cratering was observed on the 16 ply carbon/PEEK specimens, albeit barely visible, at 938N (211 lbs) of static load in the static load-deflection tests described previously. This was ~133N (30 lbs.) below the incipient damage load for the APC-2 16 ply system! Table 6.2 gives the abbreviated test results for all the 5 Joule impact tests of the 16 ply coupons and 15 Joule impact tests for the 32 ply coupons.

Noteworthy was the small degree of scatter in the data and the similarity of the plots, replicate to replicate. Values are the average of three replicates at each set of variables. Individual test results are presented in Appendix H and include coefficients of variation to demonstrate the data scatter.Individual test plots can easily be overlaid to gain additional insight into the behavior of the composites under different loading conditions. This is done by utilizing the LARPS command in the GRC 730-I data acquisition system which is described in the operators manual [Dynatup 1990].

Of the many possible overlay plots one may wish investigate, those most commonly compared are of different material systems.

Table 6.2 Incipient Damage Point Data
(16 Ply 5 Joule Impact, 32 Ply 15 Joule Impact)

Specimen ID RC = 6.35 cm annulus NRC = 5.08 cm annulus	Load, P_i (kn)	Energy, E_i (Joules)	Deflection, δ_i (mm)
APC-2 16P/RC	1.10	1.08	2.20
APC-2 16P/NRC	1.04	1.26	2.51
AS4/3501-6 16P/RC	0.75	0.54	1.54
AS4/3501-6 16 P/NRC	0.79	0.60	1.60
APC-2 32P/RC	2.84	2.06	1.44
APC-2 32P/NRC	2.92	3.10	1.98
AS4/3501-6 32P/RC	2.41	1.16	1.06
AS4/3501-6 32P/NRC	2.33	1.34	1.20

The first three overlay plots shown are of this type, comparing like systems of carbon/epoxy and carbon/PEEK at the same impact energies and common control variables. The following generalizations of these plots can be made: 1) the load to damage initiation (P_i) and deflection to damage initiation (δ_i) values (and, by integration, energy to damage initiation [E_i]) for the APC-2 systems are much higher than for equivalent AS4/3501-6 systems, 2) AS4/3501-6 systems demonstrate slightly stiffer behavior than their thermoplastic counterpart, 3) both systems tend to load in a linear manner to the incipient damage point and then lose stiffness while continuing to load to some maximum load and deflection values, 4) the carbon/PEEK systems load to a

APC-2 material exhibits a ductile, yielding behavior characteristic of a gentle decrease in the slope on the load-deflection plot. No catastrophic damage development is evident. In fact, these observations are supported by the C-scan images and visual examination which show only surface cratering and back surface doming, similar to the response in a ductile isotropic material, like 3003 aluminum. Of interest, is that the point at which this yielding begins seems to coincide with the catastrophic damage development in the AS4/3501-6 laminate. This phenomenon is seen in Figure 6.14 and more clearly in Figure 6-15.

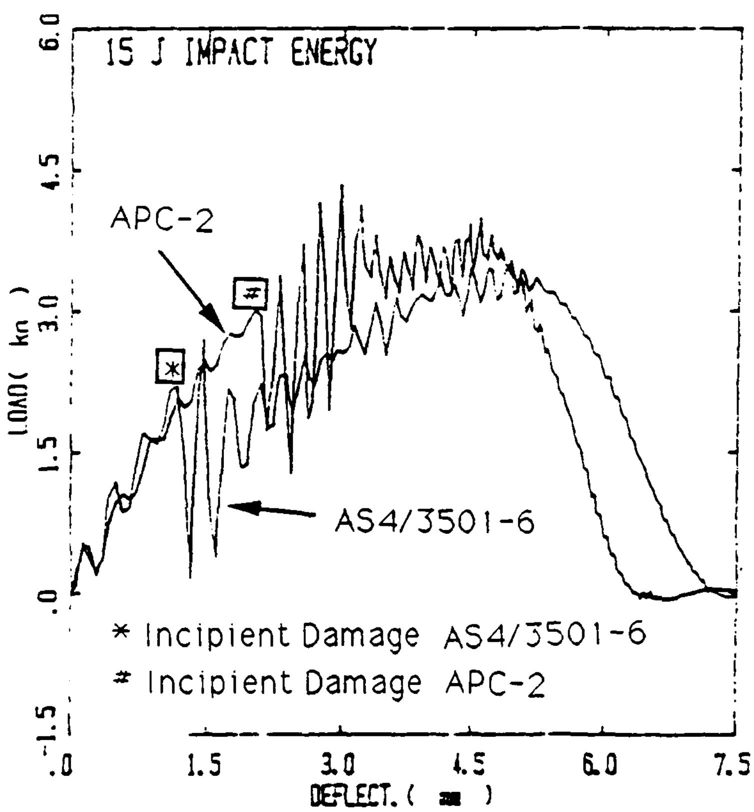


Figure 6.14 Overlay of load-deflection plot of 32 ply carbon/PEEK (APC-2) and carbon/epoxy (AS4/3501-6) [±45/0/90]4S. Incident impact energy is ~16 Joules (11.80 ft-lbs.). Tests were conducted without the reduction cylinder (6.35 cm annulus).

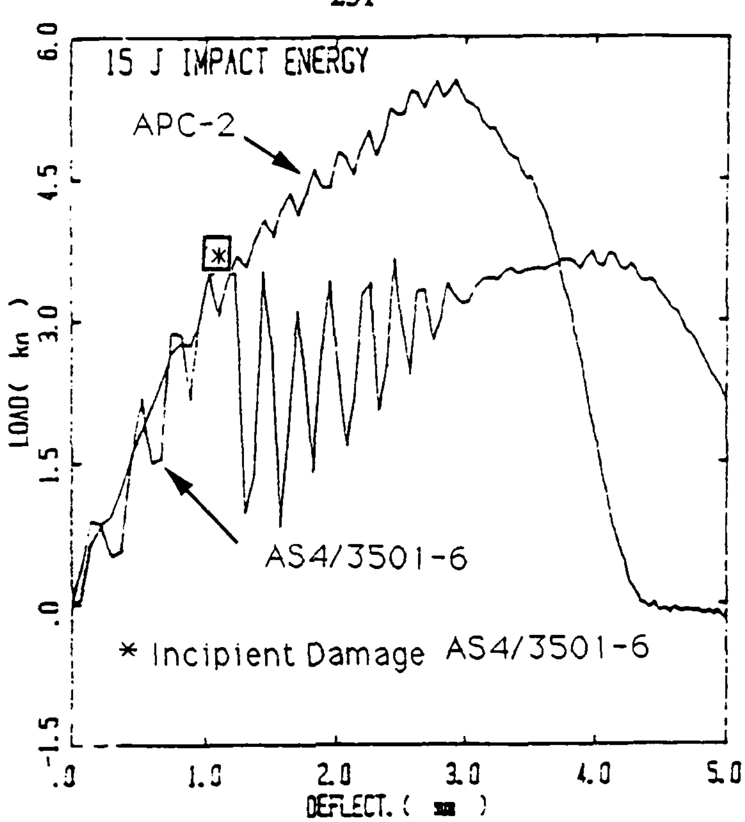


Figure 6.15 Overlay of load-deflection plot of 48 ply carbon/PEEK (APC-2) and carbon/epoxy (AS4/3501-6) $[(\pm45/0_2)_2\pm45/0/90]_{2S}$. Impact—16 Joules (11.80 ft-lbs.).

The next two overlay plots, Figures 6.16 and 6.17, show the influence of changing the annulus size for a given material system and impact energy. As expected, the smaller annulus increases the stiffness of the plate, thus, the plate deflects more; however, the incipient damage load is nearly equivalent with the larger annulus. The effect is more dramatic for the inherently more compliant (thinner and lower in-plane and flexural material constants) APC-2 plates. The extent of damage, in the load-deflection plot as well as the C-scan image was evident. More energy was available for plate bending in the case of the larger annulus tests and correspondingly less for contact loading as a function of the balance of impact energy up to the damage point.

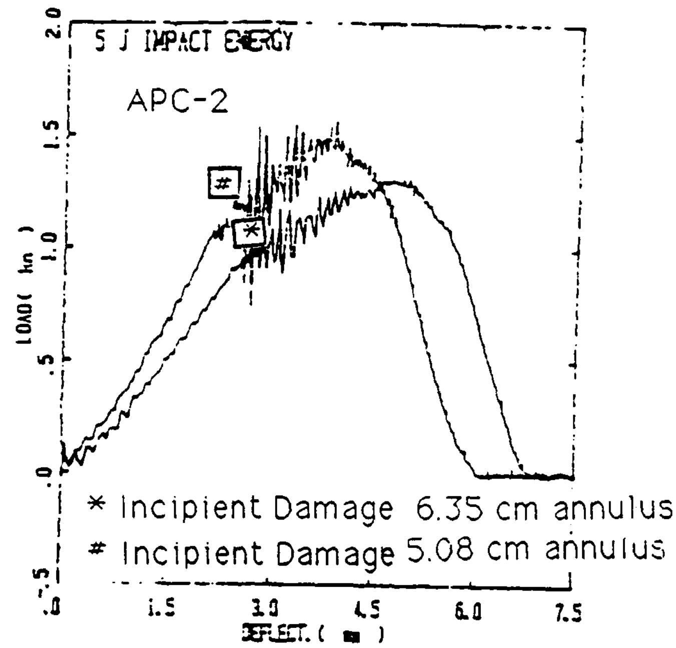


Figure 6.16 Overlay of load-deflection plot of 16 ply carbon/PEEK (APC-2) with and without reduction cylinder, annuli of 5.08 and 6.35 cm, respectively. Incident impact energies are nominally 5 Joules.

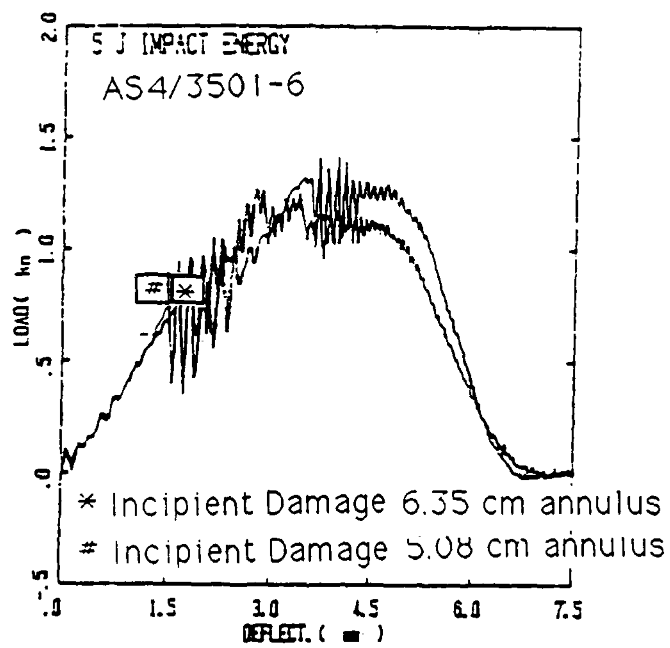


Figure 6.17 Overlay of load-deflection plot of 16 ply carbon/epoxy AS4/3501-6 with and without reduction cylinder, annuli of 5.08 and 6.35 cm, respectively. Incident impact energies are nominally 5 Joules.

higher maximum load and deflection than the carbon/epoxy system, 5) damage in the APC-2 systems is generated over a shorter deflection range and much closer to the maximum load-deflection than the carbon/epoxy system, and 6) both systems show increased durability with increasing thickness, i.e., the incipient damage point, in terms of load and deflection, increases with laminate thickness. Figure 6.13 clearly demonstrates the higher incipient damage energy of the APC-2 material system in this test setup.

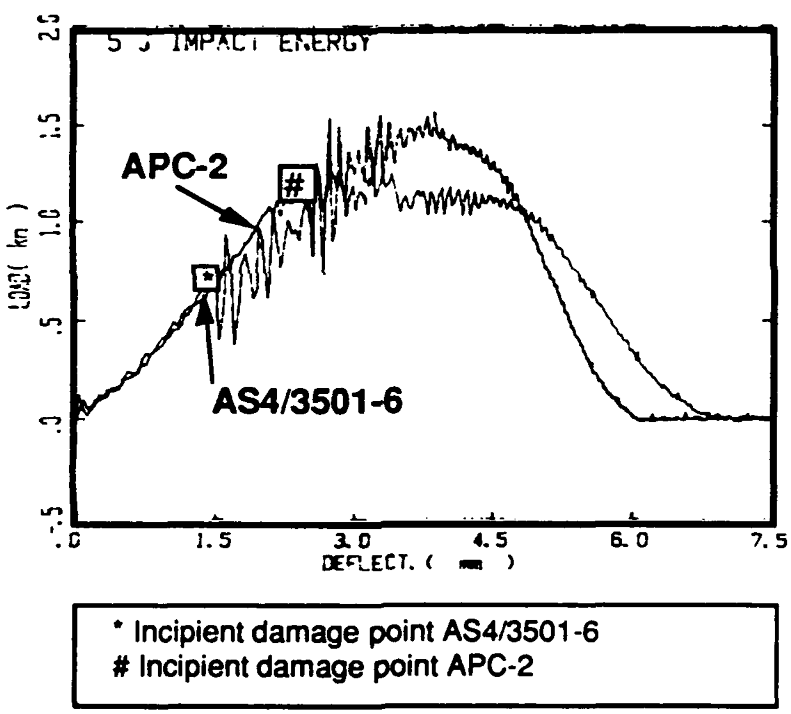


Figure 6.13 Overlay of load-deflection plot of 16 ply carbon/PEEK (APC-2) and carbon/epoxy (AS4/3501-6) $[\pm 45/0/90]_{2S}$. Incident impact energy is 5 Joules (3.69 ft-lbs.). Tests were conducted with the reduction cylinder (5.08 cm diameter annulus).

APC-2 material exhibits a ductile, yielding behavior characteristic of a gentle decrease in the slope on the load-deflection plot. No catastrophic damage development is evident. In fact, these observations are supported by the C-scan images and visual examination which show only surface cratering and back surface doming, similar to the response in a ductile isotropic material, like 3003 aluminum. Of interest, is that the point at which this yielding begins seems to coincide with the catastrophic damage development in the AS4/3501-6 laminate. This phenomenon is seen in Figure 6.14 and more clearly in Figure 6-15.

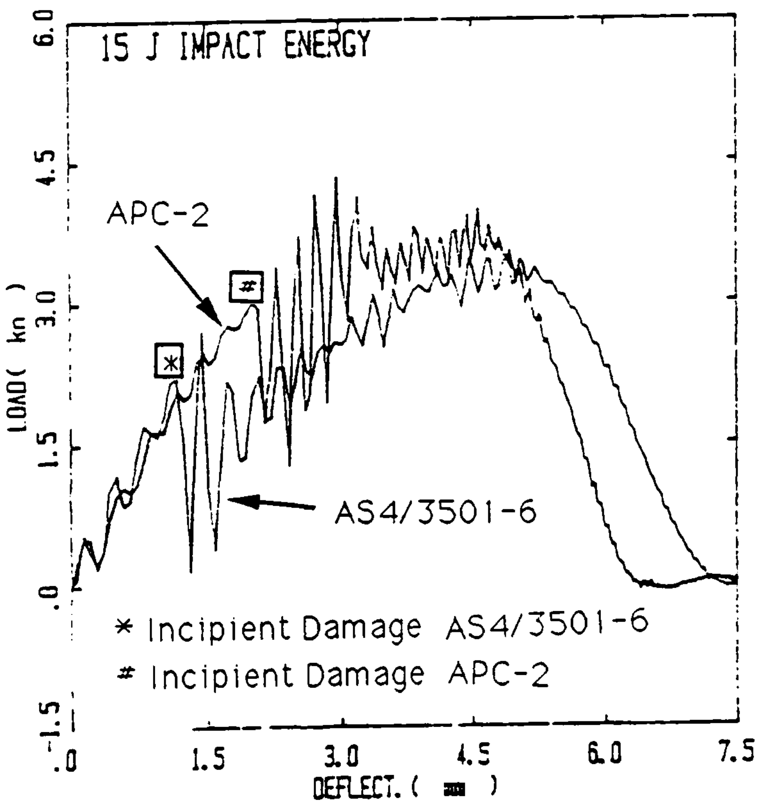


Figure 6.14 Overlay of load-deflection plot of 32 ply carbon/PEEK (APC-2) and carbon/epoxy (AS4/3501-6) $[\pm45/0/90]_{4S}$. Incident impact energy is ~16 Joules (11.80 ft-lbs.). Tests were conducted without the reduction cylinder (6.35 cm annulus).

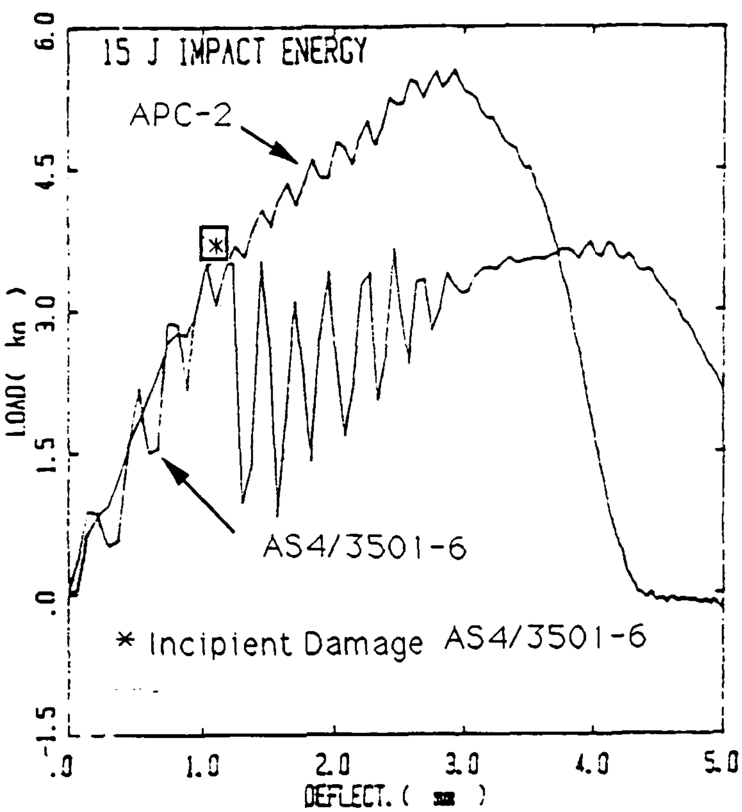


Figure 6.15 Overlay of load-deflection plot of 48 ply carbon/PEEK (APC-2) and carbon/epoxy (AS4/3501-6) $[(\pm45/0_2)_2\pm45/0/90]_{2S}$. Impact—16 Joules (11.80 ft-lbs.).

The next two overlay plots, Figures 6.16 and 6.17, show the influence of changing the annulus size for a given material system and impact energy. As expected, the smaller annulus increases the stiffness of the plate, thus, the plate deflects more; however, the incipient damage load is nearly equivalent with the larger annulus. The effect is more dramatic for the inherently more compliant (thinner and lower in-plane and flexural material constants) APC-2 plates. The extent of damage, in the load-deflection plot as well as the C-scan image was evident. More energy was available for plate bending in the case of the larger annulus tests and correspondingly less for contact loading as a function of the balance of impact energy up to the damage point.

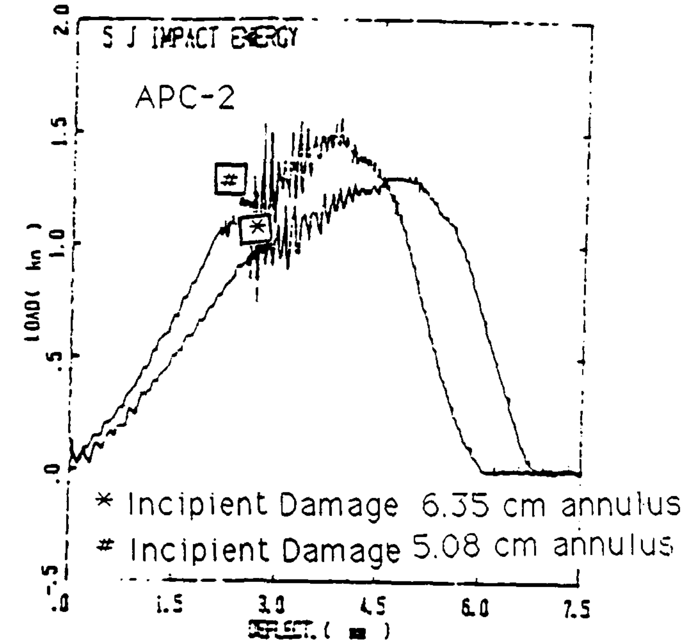


Figure 6.16 Overlay of load-deflection plot of 16 ply carbon/PEEK (APC-2) with and without reduction cylinder, annuli of 5.08 and 6.35 cm, respectively. Incident impact energies are nominally 5 Joules.

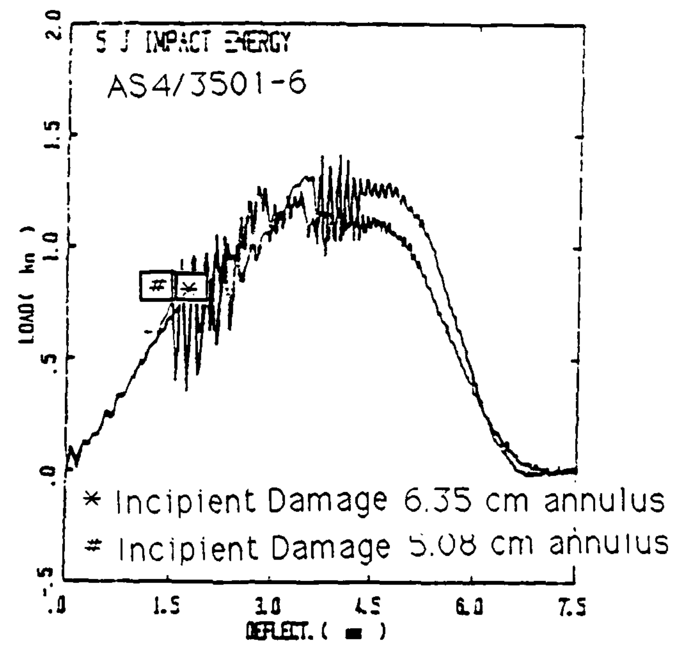
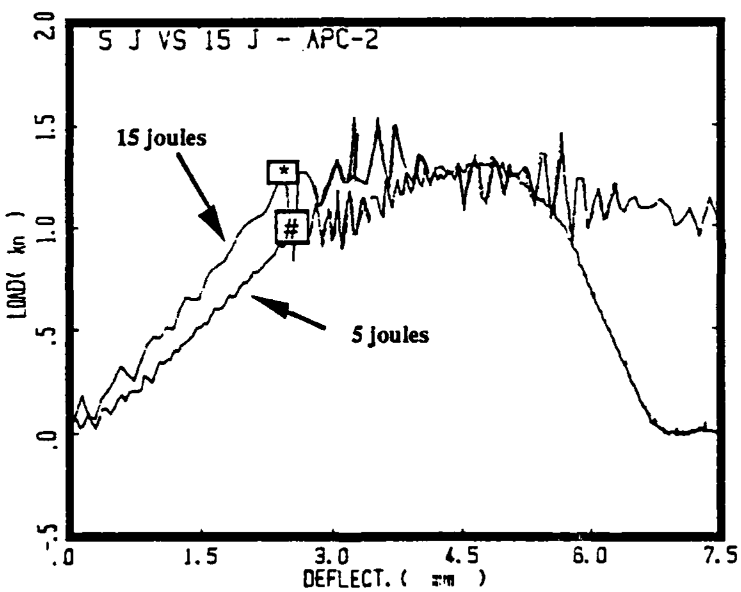


Figure 6.17 Overlay of load-deflection plot of 16 ply carbon/epoxy AS4/3501-6 with and without reduction cylinder, annuli of 5.08 and 6.35 cm, respectively. Incident impact energies are nominally 5 Joules.

Figures 6.18 and 6.19 compare tests conducted at 5 and 15 Joules with all other variables constant. Interestingly, the damage initiation point for the 5 and 15 Joule tests seemed to occur at the same deflection (this was more obvious in the AS4/3501-6 than the APC-2 coupons), while the load to damage initiation in each case was greater for the 15 Joule impact events. As expected, with regard to the damage development after incipient damage, the load-deflection responses varied considerably for the two energy levels.



APC-2 [±45/0/90]2s
* Incipient Damage 15 Joules
# Incipient Damage 5 Joules

Figure 6.18 Overlay of load-deflection plot of 16 ply carbon/PEEK (APC-2) at 5 and 15 Joules of incident impact energy. Note the stiffer response in the 15 Joule test.

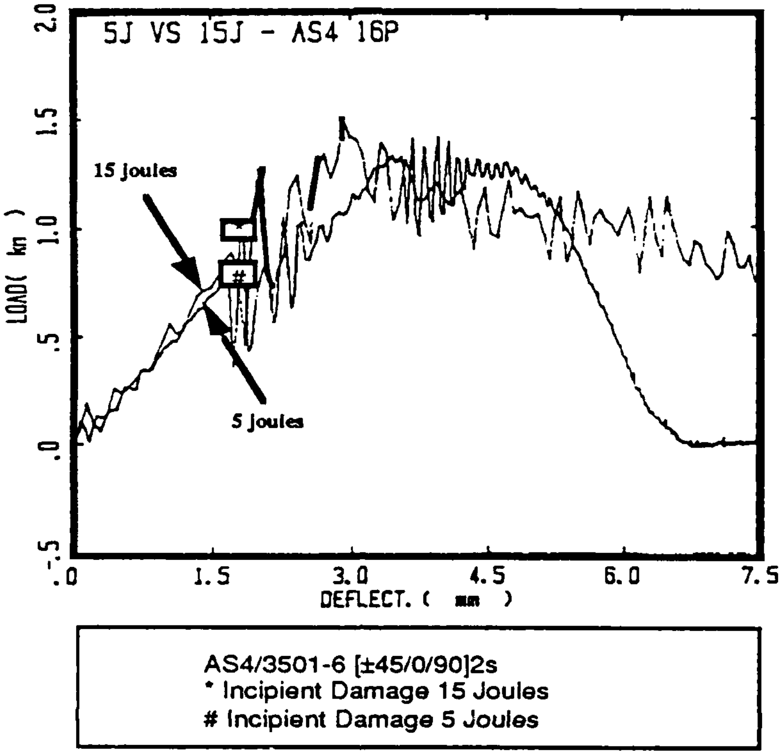
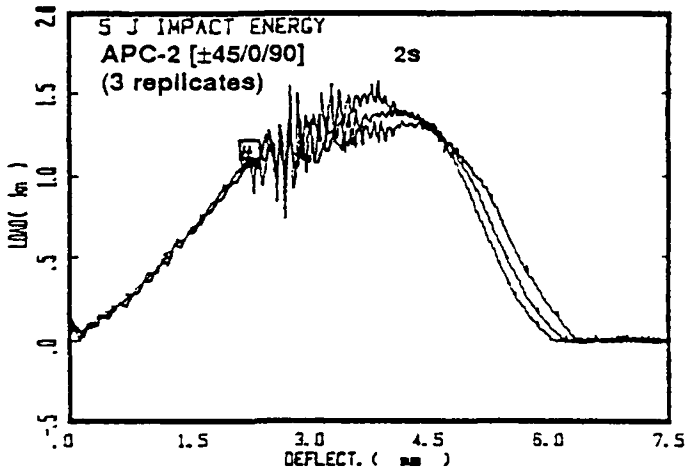


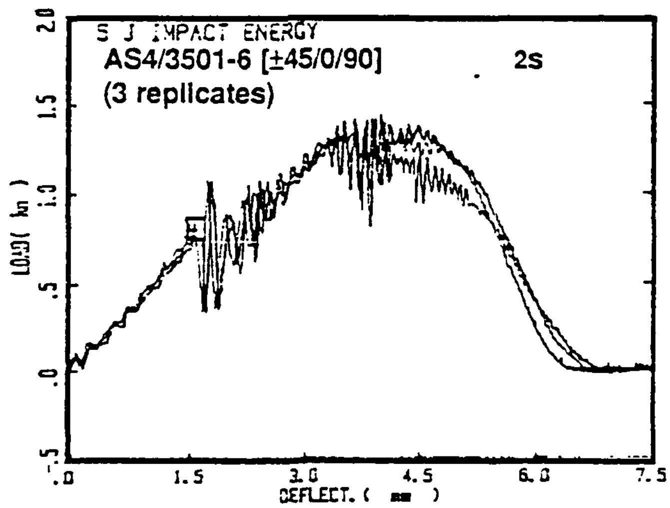
Figure 6.19 Overlay load-deflection plot of 16 ply carbon/epoxy AS4/3501-6 at 5 and 15 Joules of incident impact energy.

Finally, the overlay function can also be used to graphically illustrate the repeatability of the impact event up to damage initiation. Figures 6.20 and 6.21 show this for AS4/3501-6 and APC-2, respectively. These graphs demonstrate that not only is the incipient damage point predictable test to test, but that after this point (particularly near maximum load) the traces diverge quite dramatically, suggesting tha . less general conclusions may be made about damage development beyond this point in the process.



Incipient damage point

Figure 6.20 Overlay of three load-deflection plots of 16 ply carbon//PEEK (APC-2) tested at 5J impact energy, 5.08 cm diameter annulus. This overlay shows the repeatability in the load-deflection trace up to the incipient damage point.



Incipient damage point

Figure 6-21 Overlay of three load-deflection plots of 16 ply carbon/epoxy AS4/3501-6 tested at 5J impact energy, 6.35 cm diameter annulus.

Besides the general conclusions reached by examining the overlay plots, it would also be prudent to evaluate the static-load deflection behavior (at least to the incipient damage point) and characterize the visual, tactile and ultrasonic damage of the specimen. In general, results of these examinations have shown that internal damage (matrix cracking, fiber breakage, and delamination) occurred in the carbon/epoxy system well below any visible or tactile external damage. In fact, at 5 joules of incident impact energy, only minimal back surface fiber splitting was evident in the 16 ply AS4/3501-6 specimens despite being loaded to values approaching 200% of their incipient damage load! These results suggest that related issues of durability, inspectability, and detectability should be considered early in the design and concept evaluation process when deciding on materials, configuration, maintenance procedures, etc.

The following load-deflection plots, C-scan images, and photographs are for two representative 5 Joules impact tests. The first three figures for APC-2 16 ply, specimens can be examined concurrently to gain a comprehensive understanding of the damage development process, the detectability of the damage, and the ability to assess the damage. In this way the designer can gain a better sense of the issues relating to the use of this system in his design. Figure 6.22 is the load-deflection plot which clearly demonstrates the incipient damage point. The slightly non-linear response up to this point is likely due to the Hertzian contribution in the contact loading of the part. The damage occurring in the specimen after this point includes matrix cracking, delamination, fiber breakage, etc. To precisely say when and what type of damage is not trivial and, for the designer, probably not necessary.

The incipient damage point in the thermoplastic system is often more difficult to pinpoint precisely and occurs at much higher loads and deflections than equivalent

epoxy systems. Visible cratering may occur well below this point. The proportion of the energy going into the various modes of deformation—bending, membrane, and contact—will vary with material system, thickness, test fixture configuration, and impact location. Quantifying each's contribution is a difficult task, but may be approximated by the method discussed in Chapters 4 and 7.

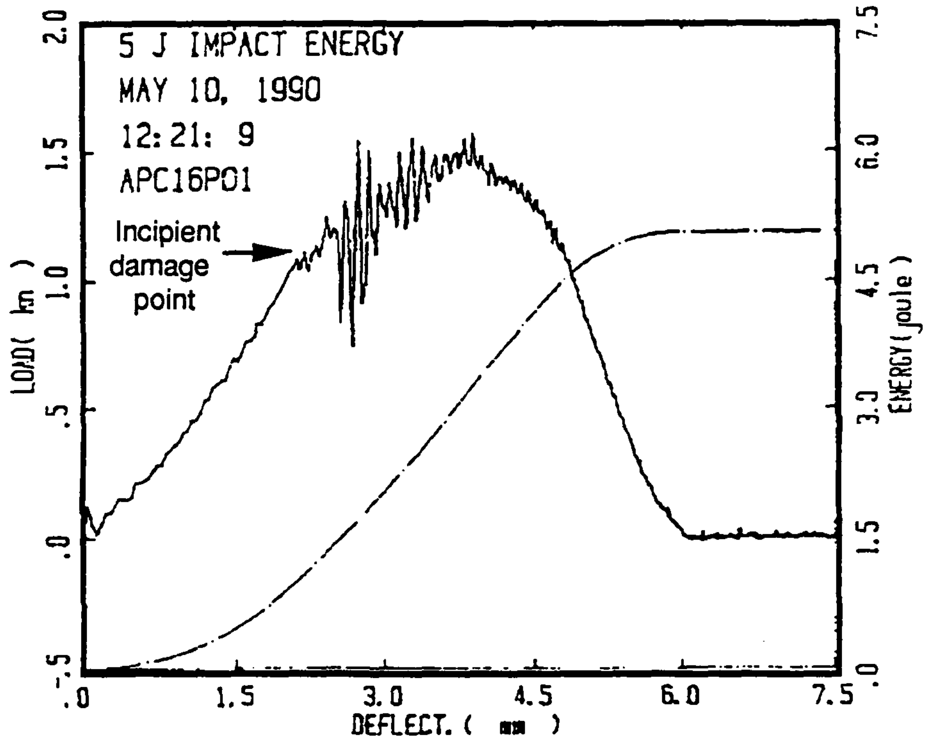


Figure 6.22 Load-deflection plot of 16 ply carbon/PEEK (APC-2) with reduction cylinder, 5.08 cm diameter annulus. Incident impact energy is nominally 5 Joules.

The corresponding C-scan, Figure 6.23, clearly reveals the damage seen in Figure 6.22 which has developed after the incipient damage point. Correlating this data sources with the photomicrograph presented earlier give a clear internal picture of the damage state.

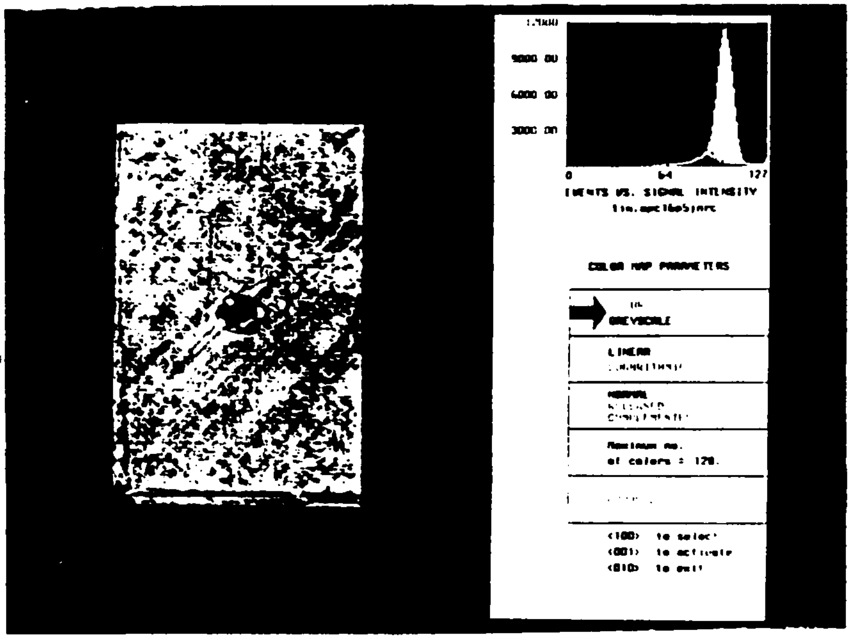
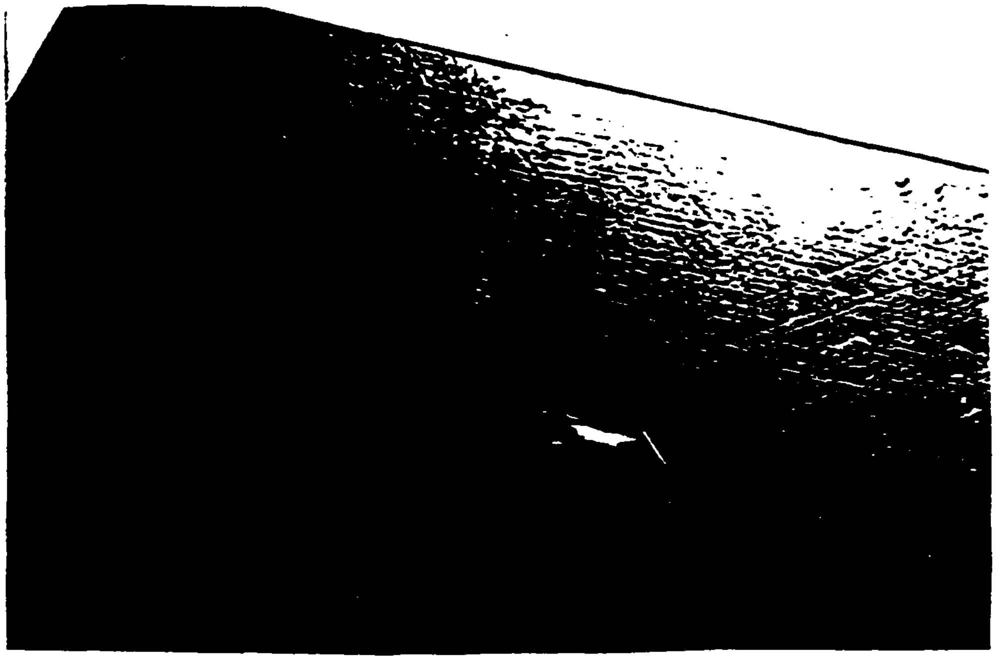


Figure 6.23 C-scan image for APC-2 impact test shown in Figure 6.22.

However, an additional piece of the puzzle is particularly of interest to the designer and his concerns for visual detectability. This is simply the visual examination of the front and back surfaces. Figure 6.24 is photographic evidence of the visible damage on the plate surface. Cratering at the contact point is clearly evident and minor radial tensile cracks at the periphery of the contact indentation are also observed.



a) Front surface—Cratering and radial tensile cracks are clearly visible, thus, easily detectable.

b) Back surface—Intraply transverse tensile microcracks are evident.

Figure 6.24 Front (impact) a) and back surface damage b) for impact represented in Figure 6.22.

Figure 6.25 is the first of a series of damage data for the equivalent AS4/3501-6 specimen. The incipient damage point is dramatically evident from the load-deflection plot. Extensive load oscillation after this point is representative of the loading-unloading cycle as damage develops—delamination, fiber breakage, debonding, etc.—and load continues to build to some maximum level.

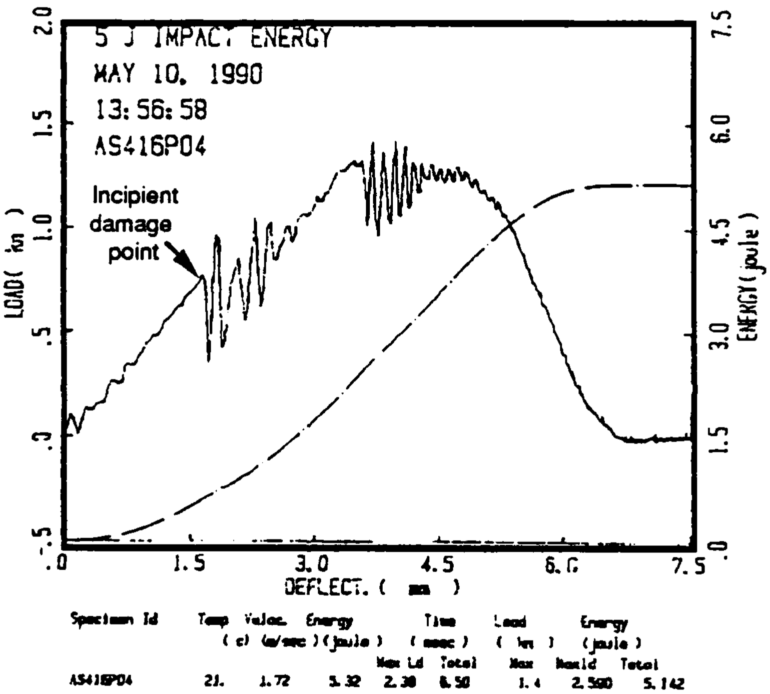


Figure 6.25 Load-deflection plot of 16 ply carbon/epoxy (AS4/3501-6) without reduction cylinder, annulus of diameter 6.35 cm. Incident impact energy is nominally 5 Joules. Note the ability of the coupon to carry load without much loss of modulus well beyond incipient damage.

The corresponding C-scan image reveals that extensive delamination has occurred through-the-thickness which will result in degraded mechanical properties, Figure 6.26.

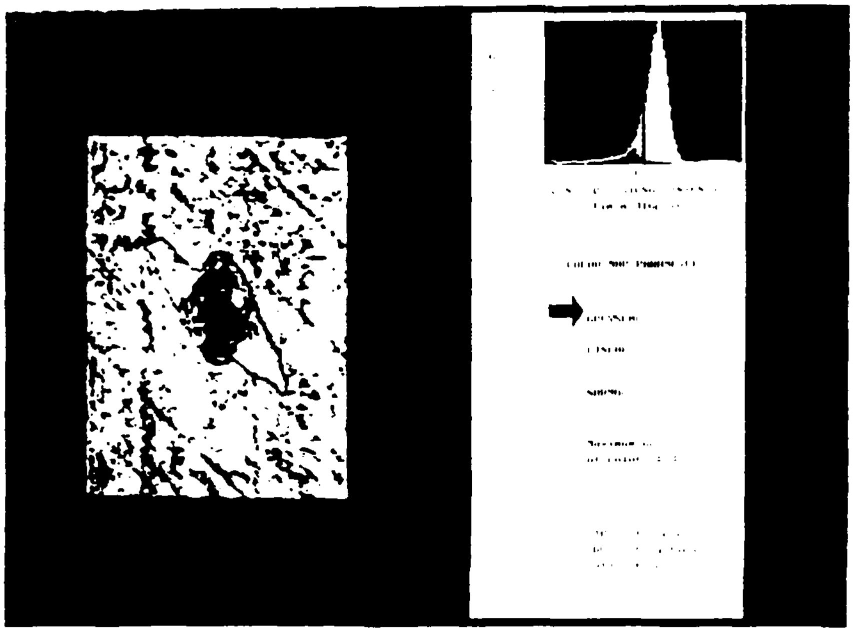
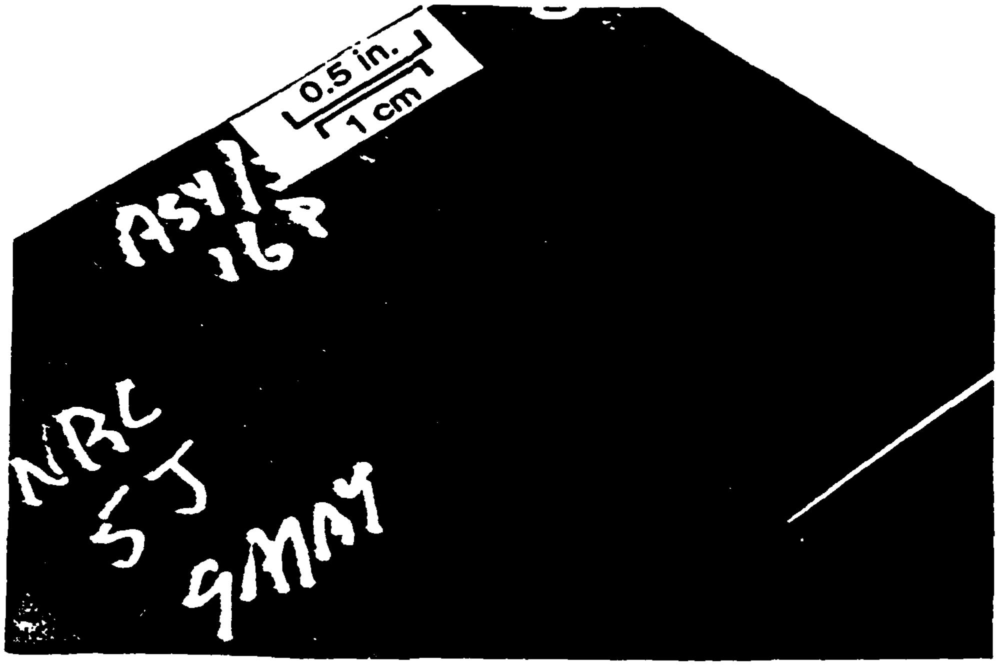
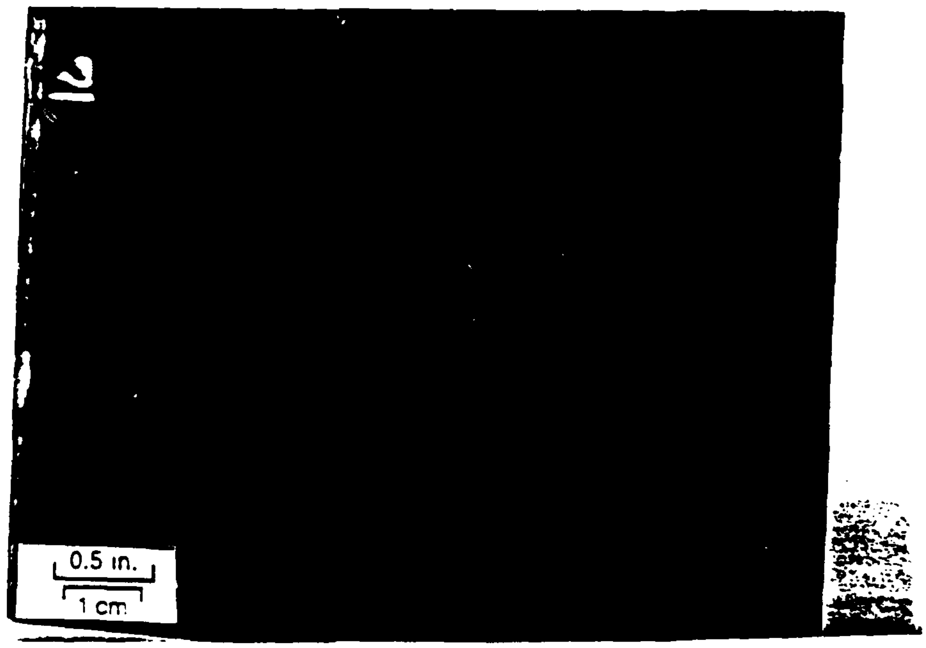


Figure 6.26 C-scan image for AS4/3501-6 impact test shown in Figure 6.25.

The impact and back surface visual examination, Figure 6.27, reveals a barely visible damage (BVID) state. It is doubtful that a visual inspection of a part subjected to equivalent loading conditions will reveal this damage, despite the extensive internal damage which have seriously degraded certain mechanical properties.



a) Front surface—The pointer highlights BVID. This would not be detected despite significant subsurface delaminations.



b) Back surface—Damage is unseen, however, last ply delaminations can be detected by touch.

Figure 6.27 Front (impact) and back surface damage for impact represented in Figure 6.25.

From the preceding discussions, and visual and graphic evidence, one can see the advantages of employing a variety of destructive and non-destructive techniques to relate damage development in composites for purposes of materials comparison and for correlation with design concern, such as inspectability, detectability, and assessment.

6.6.2 Static Load-Deflection Test Results

The goal of the static-load deflection testing, was to generate data which could be correlated with the load-deflection to incipient damage in the impact tests, and with the finite element models. Good correlations would offer support to the quasi-static assumption for low-velocity and low energy tests. (Moon and Shively [1989] reported that impactor momentum effects could be ignored for energies under 41 Joules, i.e., damage would be independent of incident momentum for a given kinetic energy regardless of mass of velocity.) Also, success in making this correlation would offer another alternative to the designer for a simple static load test procedure, using an Instron-type mechanical testing machine, for identifying the incipient damage point due to low-velocity impacts as well as offering a predictive modelling approach using quasi-static assumptions. Elber [1983, 1985] has shown, in static-indentation studies of thin circular plates (32 plies and less), that when load-displacement curves of static and low-velocity impact tests are integrated to obtain the energy absorbed in each event, that these values are nearly identical and that they follow the same general slope. This implies that rate effects are not involved in the energy absorption and damage development process. Furthermore, this implies that static testing may be used instead of impact testing at low velocities.

These tests were conducted on the 16 ply AS4/3501-6 and APC-2 coupons only, due to the loading limits in the test apparatus. Coupons were initially loaded to 102N (23 lbs.) to establish the feasibility of the test method. Three replicates were tested and load readings were taken during loading and unloading. The response for both systems was linear. After establishing the load to incipient damage in impact tests for equivalent test setups, a second set of static tests were conducted to the equivalent dynamic loads (at least for the AS4/3501-6 coupons) where incipient damage occurred. Figure 6.28 is the results of these tests for coupons clamped in the test fixture with an annulus of 6.08 cm. In the case of the AS4/3501-6 coupons cracking was heard at about 700 N (160 lbs.) of load. This was slightly below the average incipient damage load for the 5 Joule impact test. Some damage was confirmed by photomicroscopy. In the case of the APC-2 coupons, no damage was evident except for surface contact deformation, well below the incipient damage point of 1040 N (234 lbs.).

For purposes of comparison, static tests were also conducted without the top plate clamped in place, so that the coupon edges were free to bend off the surface, unconstrained by the top plate clamp. The response was more compliant as expected by correlation with a simply supported boundary condition. Figure 6.29 demonstrates this phenomenon. Again, incipient damage points are shown for comparison. The slightly more compliant response in the impact tests (which showed an essentially linear response up to damage initiation for both the thermoset and thermoplastic systems, eg., Figures 6.22 and 6.25, respectively) may result from a greater contribution of membrane reaction forces and, in the case of APC-2, an additional contribution of indentation deformation [Elber 1985].

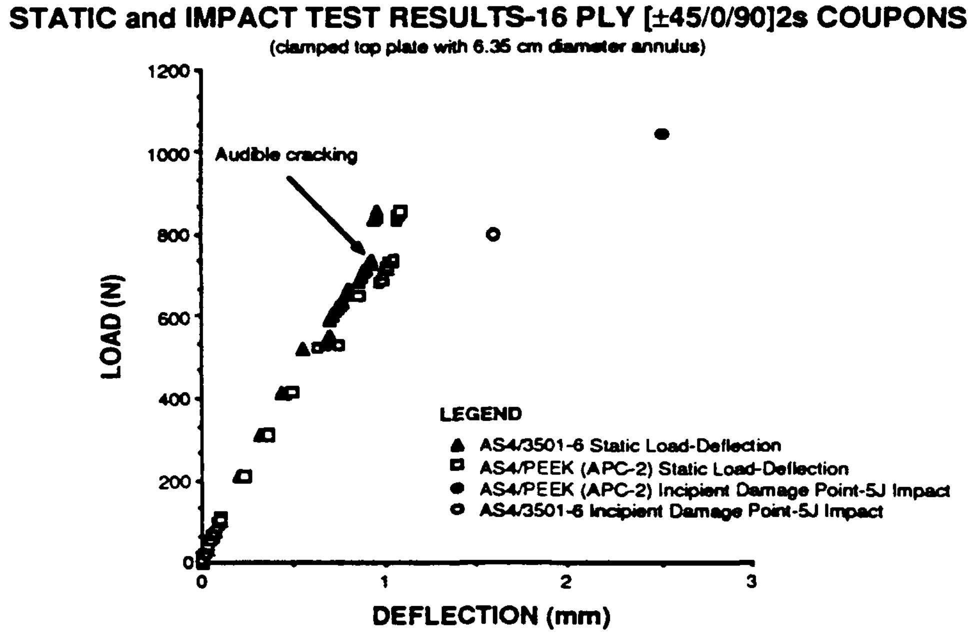


Figure 6.28 Static load-deflection (clamped top plate) and impact incipient damage points are compared. All data points are averages of three replicate tests. P-δ impact points are taken from instrumented impact P-δ trace, 5 J impact.

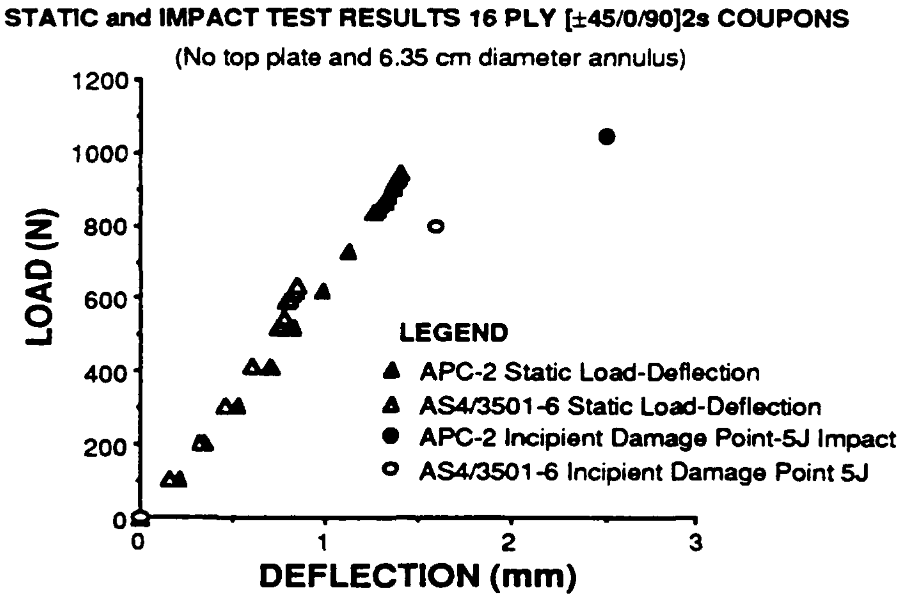


Figure 6.29 Static load-deflection response (no top plate) and impact incipient damage points compared.

These results will be explored in more detail in Chapter 7 in terms of correlations with the FE models developed in Chapter 4.

6.7 Summary and Conclusions of Experimental Results

In this chapter nothing has been concluded about the ability to use this information in a predictive way for identifying at what loads, energies, or deflections incipient damage may occur in a real structure. The information gathered from these tests, however, is certainly instructive to the designer in terms of what may be expected from the response of these types of systems. Clearly, the value of focusing (as a first approximation) on the incipient damage point in a material system seems a reasonable first step in assessing the durability, if not the damage tolerance of the composite. The information from these plots is valuable in the sense discussed in Chapter 4 since it provides data to be used for correlation with load deflection responses in modeled structural concepts.

Chapter 7 describes the author's attempt to correlate the models developed in Chapter 4 with the experimental results discussed here (static and instrumented impact tests) in a manner which will provide a first order technique to predict incipient damage in real structures. Assumptions used are that behavior is linear-elastic up to the incipient damage point and the static load-deflection response is equivalent to the dynamic load response up to the incipient damage point. These assumptions proved difficult to support in certain instances, particularly with the thermoplastic system, as plastic deformation in the contact zone was clearly evident at very low loads. But better fit did result with the brittle epoxy laminates. Despite this seeming difficulty with the APC-2, since damage is clearly visible in the thermoplastic systems well below incipient

damage, an "assess and repair if detected" design criteria for these systems would seem a reasonable approach. Furthermore, when dealing with very thin laminates are and/or when deflections exceed the laminate thickness, the non-linear membrane action must also be considered. More sophisticated models which take into account the nonlinear behavior of these systems would be required for the development of predictive criteria.

Despite these complications, the use of the 90° critical strain value of the composite seems to be a reasonable first estimate of low-velocity impact damage in the case of thin plates, < 32 plies, where plate bending dominates the target response. Furthermore, since the plate bending response can be relatively easily modeled, once the structural configuration and constraints are known, and a prediction of the impact events (loads) likely to occur can made by the designer, predicting when damage might occur in a structure for a given set of input variables should be straightforward.

CHAPTER 7

CORRELATIONS OF EXPERIMENTAL RESULTS WITH FEA

$(x + y)^2 = x^2 + 2xy + y^2$ ... *Therefore, God exists.*

Euler

7.1 A Review of the Testing and Analyses Conducted

In Chapter 4 the author described an approach for using microcomputer-based FEA of a local point loading on a structure (to account for plate bending and structural compliance) combined with a local force-deflection analysis (to account for Hertzian indentation behavior) to determine the local through-the-thickness stress state of a composite part. This resulting stress profile could then be assessed for failure based on a particular failure criterion against a given impact event.

The analytical approach for this modeling was essentially developed by Greszczuk [Zukas 1982], however, with the advent of inexpensive and user-friendly FEA software, the approach has been expanded here to account for the global

contributions of the structure in a way that analysis based on idealized plate models cannot. Using equations derived by Greszczuk [Zukas 1982] and static indentation work conducted by Bostaph and Elber [1982, 1983] a predictive methodology, for determining when impact on a structure may result in incipient damage, was developed using quasi-static assumptions and a static load-deflection analysis for low-velocity impact.[1] The low-velocity impact threat analysis is determined using the House of Quality techniques discussed in Chapter 3. From this analysis, impactor configuration, materials and dynamic properties are predicted for a given application. FE models of material and structural concepts to meet these threats are built (Chapters 3 and 4), and experimental data from instrumented impact testing and/or static load-deflection tests (Chapter 6) based on critical response variables are generated (Chapter 5). An energy method may be used to determine the local force distribution in the area of impact.

The methods and results of Chapter 4 provide us with predictions of the plate bending response for isotropic or quasi-isotropic materials. Since these are largely determined by the in-plane properties of the materials (at least as a first order approximation—normally accurate enough given the uncertainties which exist early in the design cycle) a laminate analysis package, such as CMAP or GENLAM may be used. For more conservative estimates of the plate bending response the flexural constants should be used. Hertzian indentation behavior is a local response which depends on the material properties of the impactor and target; and the local structural properties, such as radius of curvature of both, but, as has been stated, the plate bending

[1]A very elegant and sophisticated modeling approach to this problem for higher velocity impacts (10 to 200 m/sec) has been described by Cairns [1987] in which he clearly develops the importance of insuring that the structural contribution to the local impact response be included in any analysis.

load which is generated during the impact event and is dependent on the global structural configuration, is the same load which generates the Hertzian indentation behavior. Therefore, if this load is known (or predicted) then the Hertzian deformation may be readily computed. Depending on the problem to be solved, one may enforce either loads or deflections in the global FE model to get their counterpart in the results and compute the input energy by integration, or one may use incipient load and/or deflection information from an impact test using concept materials and apply those to the model to determine generate load/deflection/and energy data which can be used in design. This may require iterations of the problem to generate the critical loads and/or deflections for achieving the failure stress state which combines both the plate bending and Hertzian response.

If one assumes a stationary target, an isotropic rigid spherical impactor where $E_{impactor} >> E_z$ (of the target material), and that the contact behavior is dominated by the properties of the matrix, then the Hertzian contact indentation may be easily calculated if the total load is known. In the case of FEA with MSC•PAL 2, if nodal enforced displacements are applied, then the program computes reaction forces and moments as well as shear, normal, and combined stresses based on a variety of failure criteria.

The physics of the problem can be described by Equation 4.12, shown again for convenience

$$\tfrac{1}{2} m_1 v_1^2 = \int_0^{\delta_{max}} P_p \, d\delta_p + \int_0^{\delta_I} P_c \, d\delta_I \qquad (1)$$

where m_I is the mass of the impactor and $P=P_p=P_c$ is the total load at the point of impact. Recall that the first term on the right hand side of the equation is the plate bending term and the second is the indentation contribution. But, this equation is for the total impact energy and assumes no contributing energy absorbing factors, such as, structural compliance. In real structures, the force energy balance must include a term for this compliance (and as discussed in Chapter 4, perhaps, many other contributions, elastic and otherwise).

$$\frac{1}{2} m_1 v_1^2 = \int_0^{\delta_{max}} P d\delta_p + \int_0^{\delta_I} P d\delta_I \int_0^{\delta_s} P d\delta_s \qquad (2)$$

where the third term in the right hand side of the equation represents the elastic energy absorbed by the structure. If the structure is very compliant, as shown in the case of the impact tower with the Jello base, then this term is significant and relieves the other terms from energy absorbing duties. In an analytical plate solution, there is no contribution for this term where rigid clamped or simply supported boundary conditions are assumed. In an extremely rigid impact test fixture this term can, likewise, be neglected, assuming setup and installation are controlled and understood. So, we know, given the results from Chapter 4, that the load-deflection response in the experimental studies and modeling of the AS4/3501-6 and AS4/PEEK (APC-2) is determined by the plate bending and Hertzian contributions as well as any unusual action at the annular clamped boundaries on the test plates.

These "true" boundary conditions are simpler to represent in the FE models by adjusting the annular boundaries and plate fixity conditions to more closely approximate actual plate clamping. This essentially involves either modifying connectivity between the annular boundary and the plate, or the use of connective

elements which can modify the plate response to more closely coincide with the experimental results. In this study, the author observed the reaction of the plates under these modified conditions and compared these experimental observations to determine if the modifications to the models seemed reasonable. In some ways, these modifications may be viewed as self-fulfilling prophesy in that they are made to correlate with experimental results, therefore, they must be done prudently and judiciously. Ideally, impact test fixtures should closely represent ideal boundary conditions or at least have mechanical fixity which is relatively easily modeled. This was one area which presented difficulty to the author in modeling the Dynatup test fixture.

But, the incipient damage point identified in the experimental results of Chapter 6 occurred at levels considerably below the total kinetic energy of the impactor. Therefore, since many non-elastic modes of deformation occur after this point in the impact event, one must concentrate on the impact event up to this point to keep the analysis tractable. The experimental results of the energy, load and deflection to incipient damage are necessary to give predictive values; to be used in the analytical and FE models for determining the actual load-deflection response in the real structure which will result in damage. Obviously, candidate material systems developed in the Pugh concept selection process would be used to generated this data.

One focuses on the energy to incipient damage in the test procedure. Assuming elastic response to this point, i.e., no damage development or plastic deformation, the latter being a poor assumption for the AS4/PEEK system. This response may or may not be linear elastic depending on the contributions of the Hertzian behavior and membrane action. One can express the energy-force balance as

$$E_i = \int_0^{\delta_p} P_i d\delta_p + \int_0^{\delta_I} P_i d\delta_I + \int_0^{\delta_s} P_i d\delta_s \tag{3}$$

where E_i is the incipient damage energy, δ_p is plate bending deflection, P_i is the load at incipient damage, δ_I is the contact indentation, δ_S is the structural deformation, and $\delta_T = \delta_p + \delta_I$ is the total local deformation at the impact point. From the instrumented impact tests we know E_i, P_i and δ_T. P_i and δ_T were also determined from the static load-deflection tests. δ_S was shown to be negligible—2 to 3 orders of magnitude less than dp—by FEA. δ_p can be back-calculated by the difference of δ_T and the calculation for δ_I, or it can be gotten experimentally by a back surface deflection reading from an analog dial indicator apparatus or, as described by Bostaph and Elber [1982], a DCDT apparatus which they used with a hydraulic pressure ram for static load-deflection measurements of thin composite plates. Incipient damage point data are presented in Appendix H.

7.2 A Model for Using Impact Test Data in Impact Design—A "Cut and Paste" Approach with FEA

Since the structural configuration and constraints (along with the material properties) will determine the loads and deflections generated for a given input energy, one can use the P_i/δ_i data generated from the experimental work as input to the FEA to determine in-plane stress states at a given location on the model for a local low-velocity impact event. The steps to this approach would be as follows, assuming the completion of the House of Quality phase of the design, the generation and testing of material concepts, and the generation of candidate structures.

1) Build a FE model of the structure.

2) Enforce Pi (δi) (from instrumented impact test) on the model in the location(s) of expected impact to generate corresponding P (δ) and stress states. These data are generated based on some statistical prediction of the maximum impact energy expected.

3) Calculate the Hertzian contact deformation analytically based on the resultant loads (deflections).

4) Calculate the energy to generate this combinations of loads (deflections) and the stress state in the structure at this point using FE's.

5) Determine when and where failure will occur based on maximum stress and/or energy distortion method.

If, based on these results, incipient damage does not occur for the predicted low-velocity impact event, then the structure should be evaluated for the kinetic energy of the impact event which will generate maximum loads(deflections) and assess for impact damage.

As the local response becomes stiffer, the structure will be able to absorb less impact energy and the stress state will be dominated by Hertzian behavior. This is demonstrated in the thicker specimens and, for impacts, at or near stiffeners where plate bending is suppressed. In these circumstances, matrix toughness and interlaminar shear properties seem to be most critical to impact resistance. Conversely, plate bending dominates the failure when bending is possible and impact velocities are relatively low, < 10 m/sec. Where plate bending, δp, is greater than 1.5 to 2 times the plate thickness,

membrane action is important and fiber failure strains become the dominant failure criteria. In these cases tougher resins seem to do little to improve impact resistance [Elber 1983]. The plate bending and Hertzian contributions to the total defomation of the quasi-isotropic coupons used in the study are shown in Figure 7.1 for the load range used in the static load deflection tests.

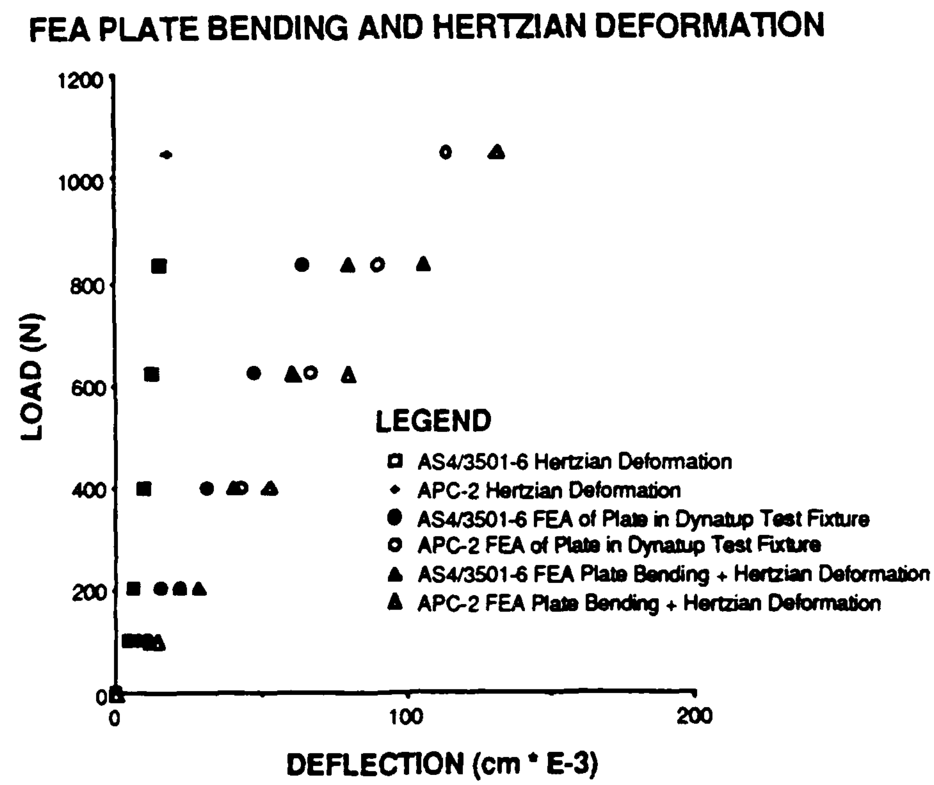


Figure 7.1 Load-deflection analysis of 16 ply AS4/3501-6 and AS4/PEEK coupons. Both the plate bending contributions from the FEA and Hertzian deformation (described in Chapter 4) are shown.

The power relationship for the Hertzian deformation is clear. The figure reflects a strong contribution from the Hertzian deformation. This is due to the dependence of this contribution on the more compliant resin properties, relative to the impactor properties. Hertzian deformation was calculated using Equations 4.3, 4.4, 4.5, and 4.6. A steel tup (E=30msi, υ=0.30) with radius, R_1, 0.635 cm was assumed. The resin properties used are presented in Table 7.

Table 7 Resin Properties Used in Calculation of Hertzian Contact Deformation

RESIN	E_m, GPa (msi)	Poisson's ratio,υ
EPOXY	3.45 (0.50)	0.35
PEEK	3.5 (0.51)	0.42

It is likely that the incipient impact data generated from instrumented impact tests will represent conservative estimates of the real structure's ability to carry these loads; therefore, one may iterate the above procedure for ever-increasing loads (deflections). However, taking a maximum-expected-input-energy approach will allow the designer to bracket the impact event for the incipient energy level in the real structure. It makes little sense, from a design viewpoint, to assess the impact resistance of the structure at some arbitrary energy level, well above that expected to occur in service, unless one must apply a conservative design criterion due to damage tolerance consideration. A better design approach is to build damage tolerance selectively into the structure where it is required so that the structure operates safely until damage is detected and repaired. At the constitutive, lamina, and laminate level; materials, stacking sequence, and ply orientation will influence load-deflection response and stress

allowables through-the-thickness. These factors would be assessed at an appropriate point in the impact design methodology (see Chapter 3).

7.3 Correlations of FEA, Static and Impact Test Results for 16 Ply AS4/3501-6 and APC-2 Coupons

In this section, the correlations of impact and static tests, and FEA results for 16 ply AS4/3501-6 and AS4/PEEK specimens are described. The results of each of these tests and analyses were presented in Chapters 4 and 6. The purpose of this section is simply to verify the ability to accurately model the load-deflection response of the actual impact test. If this is possible, within reasonable assumptions and approximations, then extension of these models to real structures may be done with the degree of confidence required for a global-local load-deflection response and determination of the resultant stress states.

The FE model of the Dynatup test fixture with 6.35 cm annulus and 7.62 mm x 10.2 mm coupons of AS4/3501-6 and APC-2 plates as shown in Chapters 4 and 6. The full 3-D tower model was not used because 1) its extreme rigidity allowed one to disregard its load-deflection contribution in the global response, and 2) the additional model size would increase the time to analyze the load cases. The test fixture was used so that annular connectivity could be controlled to allow membrane flow at the boundary, and the response at plate edge could be observed. With the full 3-D model asymmetries in boundary, conditions could easily be introduced which would represent variations in clamping force, for example, for off center loads.

The static load-deflection response for these same coupons in the identical test apparatus are also presented for comparison. Finally, these FEA and static test results are compared with the incipient damage points from the 16 ply, 5 Joule impact tests and 15 Joule tests. Figure 7.2 shows results for the AS4/3501-6 coupons. It is quite apparent that, while the absolute deflections for all three cases are very small at these loads, there is still some divergence in the results as one goes from the stiffer response in the models to the greater compliance evident in the impact test results. The agreement between the analytical results and the static load tests is excellent.

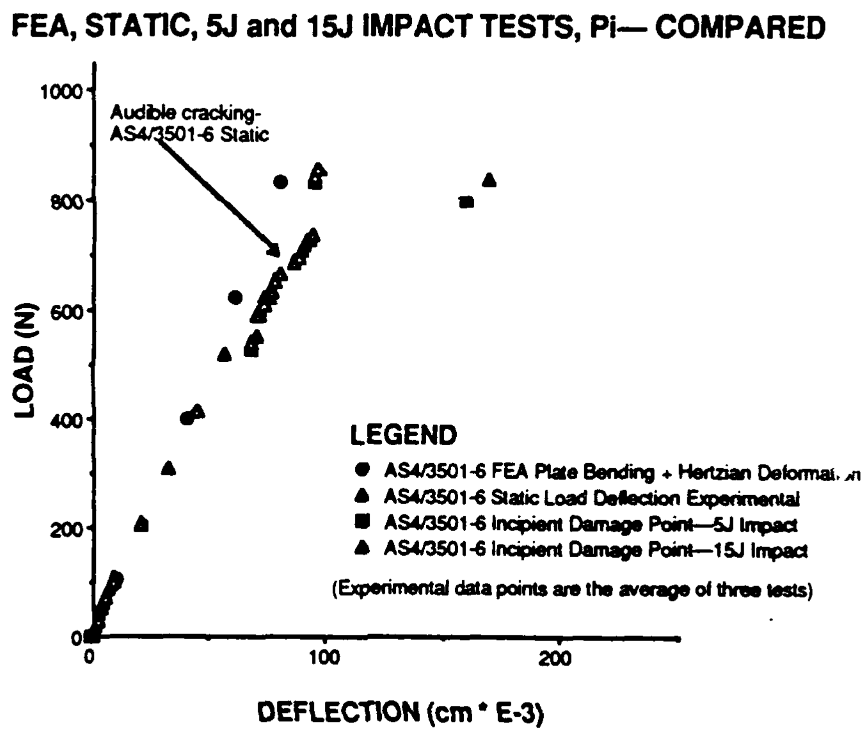


Figure 7.2 Comparison of FEA, static load-deflection and impact test results for 16 ply AS4/3501-6 composite plates. A 12.7mm steel tup was used for static/impact tests.

Similar data for the APC-2 coupons are presented in Figure 7.3. The incipient damage points for the 5J and 15J levels occurred at about the same energy, however, at correpondingly higher loads and lower deflections. This suggests at low velocities and energies that a characteristic incipient damge energy, E_i, does in fact exist.

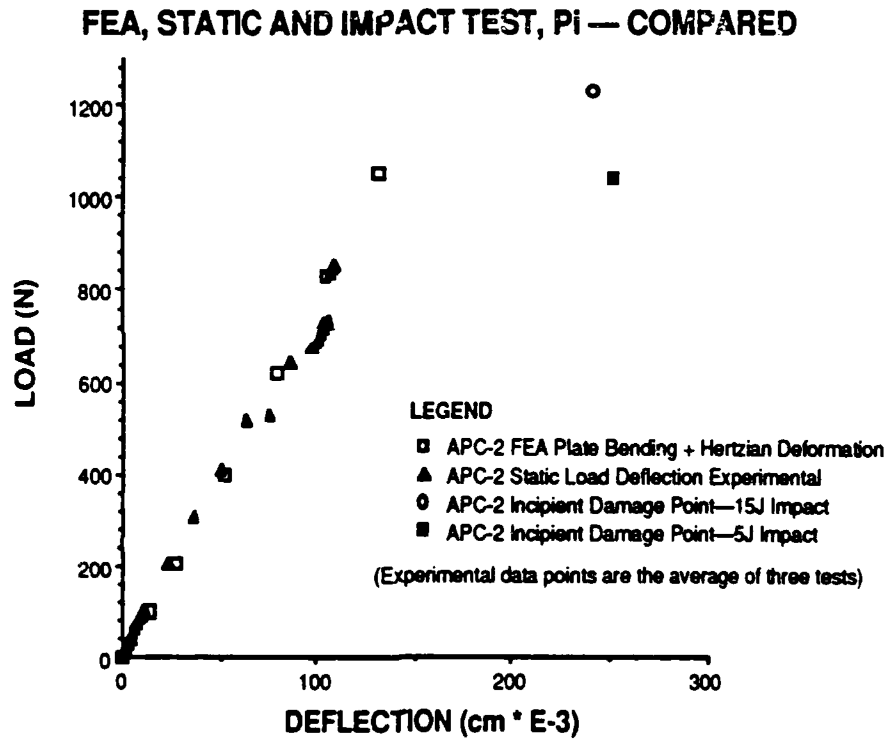


Figure 7.3 Comparison of FEA, static load-deflection, and 5 and 15J impact test results for 16 ply APC-2 specimens.

Generally, agreement between the modeling and static test results is very good. Variations between these results could be attributed to a variety of factors:

1) Simplifying assumptions concerning use of in-plane properties only for plate bending response (For these materials they would show a stiffer response than the actual tests.)

2) Improper boundary conditions or other model anomalies do not take into account membrane slipping during the testing.

3) Plastic deformation in impact and static tests at very low levels. These influences were shown by visual observation to be significant for the thermoplastic material. As noted previously, loads above 450 N (100 lbs.) in aluminum result in divergence due to plastic deformation. It is possible this occurs as well in the composite materials particularly the PEEK resin systems.

4) Simplifying assumptions about the Hertzian contact indentation controlled by E_Z.

5) Damage development (reduced stiffness) below incipient damage point, which is not identifiable in the impact test due to noise in the signal. (This is unlikely to be a problem given the truly linear response in the load-deflection plot of the impact test data.)

6) Course FE model resulting in inaccurate values. (It is unlikely this is the problem as the author verified this model with aluminum material

properties in Chapter 4 and found it to correlate well with analytical and test results.)

The variations between the static load-deflection response and the impact load-deflection at incipient damage are less easily explained. While the static test apparatus was calibrated and the sources of error identified and measured, it is possible that this rather simple measurement technique could have resulted in inaccurate readings. On the other hand, response was generally linear to damage, as predicted, given that total deflections read were small and included both plate bending and Hertzian contributions.

In any case, from a design viewpoint, the load-deflection models with Hertzian contribution can provide a conservative estimate of the allowed deflections in the part for a given load level when coupled with the incipient damage point as determined by the instrumented impact test, itself conservative.

A follow-up procedure using a linear variable displacement transformer LVDT could be used to verify these static measurements. As noted by Greszczuk [1982], for aluminum plates loaded above 100 lbs, some plastic deformation is being generated. It is also possible that, even at low velocity, some impulsive loading locally contributes to a greater contact deformation than would be generated by the static load deflection in the AS4/PEEK material. The static load-deflection and impact test results for the AS4/3501-6 showed much better agreement.

7.4 Discussion and Conclusions

In this chapter, a method for using impact test data directly in design of composite structures, rather than simply for material screening, has been described. This method takes advantage of the notion that the physics of low-velocity impact events allow one to disregard momentum effects and treat them quasi-statically. Because of this, the impact event may be decomposed into plate bending and global contributions (modeled by microcomputer-based FEA) and local Hertzian contributions (calculated analytically). Reasonably good agreement between static and impact test data and FEA at loads representative of those experienced dynamically in the impact event has shown, for the systems studied, that this an adequate approach for first order analysis early in design. Knowing these loads and the loading function the triaxial multilayer stress state through the laminate can be determined and a failure criterion applied to determine failure.

The generation of incipient damage point data for the materials systems and energy levels of interest has been shown in Chapter 6 to be reasonably straightforward, given an appreciation for the role the impact apparatus may play in determining these results. This data is then used directly in terms of loads and/or deflections enforced on the structure to develop design stress allowables for the structures of interest and to evaluate competing structures for these stresses developed by this type of loading. Complications in this approach develop when fully anisotropic materials and complex geometries are involved. Furthermore, additional thermomechanical preloads, residual stresses, and process-induced flaws all add levels of complication. These could all be treated with more sophisticated analyses, but are beyond the scope of this study; which

is to develop a tool for the preliminary design stages which combines impact and static testing, and simple modeling to predict the onset of damage in composite structures subjected to low-velocity impact.

The good correlation of static load-deflection data with the FE models and the incipient damage point from the impact tests suggests that our assumptions regarding the use of static test and analysis methods for low-velocity impact damage are valid. With this knowledge the author reiterates the approach which the designer could take in assessing his structure for impact resistance assuming a rigid impactor, low-velocity (< 10 m/sec)/low energy (< 40 Joules) impact, and plate bending dominates:

1) Use 90° flexure tests for a first order estimate of impact strength based on a ε_{90° critical strain value. Failure in these situations is matrix dominated, thus, this value will provide a conservative lower bound of performance for the structure.

2) The next level of sophistication would employ the "cut and paste" method of using FE modeling to determine the structural compliance (eg., plate bending contribution) based on either enforced local load or displacements and calculation of the Hertzian contribution to determine the total local deformation and compare the resultant energy with the incipient damage energy of either an instrumented impact test or a static load-deflection test.

3) A wide range of impactor and target materials could be analyzed in the above manner to provide the designer with predictive impact damage data.

CHAPTER 8

SUMMARY AND CONCLUSIONS

Much too easily our Western; reductionist science looks only at the parts of things. We still assign the study of sand to the geologists, and we assume the wind is the domain of meteorologists and that plants are for botanists, when what we need desperately is more people who understand dunes.

Tom Horton [1987]

(from Bay Country: Reflections on the Chesapeake)

8.1 Reflections on Impact Design Research

When one endeavors to do "engineering design research" one must, if one is honest with the definitions of design as they are presented in this thesis, be prepared to investigate the breadth of the topic rather than delve deeply, in the traditional reductionist manner, into a specific problem of academic interest. Design research, almost by definition, must have some utility to the designer, product manager, process engineer, working engineer, material scientist, and, ultimately, customer if it is to be meaningful or worthwhile. In a sense, at least from the perspective of the academic experts in the particular area studied, this approach may doom it to the realm of the trivial, mundane, or perhaps, even quixotic of scientific enterprise. Willing to suffer these,

perhaps justifiable, criticisms the author undertook to "spread out" into the area of low-velocity impact in composites in an attempt to understand the global problem from a materials, structural mechanics, and design point of view. The challenge was to provide to the customers of this thesis a set of tools or, at least, some insight which could be used to improve the impact resistance of the composite products they make, sell, and use.

While issues of design methodology and impact testing were investigated, many others, such as the roles of process induced flaws and environment on the impact resistance of composites, were not; although their importance is appreciated and should not be underestimated by the designer. Hopefully, worthwhile contributions resulted from the work. (Certainly, the author has a much better appreciation for the complex variability of designing with composites, in general, and designing in impact resistance, in particular.)

Since each chapter included a brief summary and conclusions, the purpose of this chapter is to briefly highlight and underscore, and, if it is not already clear, show the connection between the various parts of this work. The author's assessment of the degree to which the research goals (presented graphically in Figure 1.3, the author's "mind map") were reached is in the following section.

8.2 Significant Accomplishments and Key Observations

A, perhaps, obvious conclusion about designing composite structures for impact resistance is that there is no "silver bullet," i.e., no one or combination of methods or techniques is either necessary or sufficient to produce some ideal impact

strength. Low-velocity impact damage in composites is a recognized impediment to their full acceptance and use given its deleterious (in terms of residual strengths) and insidious (in terms of detection and assessment) nature. However, as noted in Chapter 2, significant progress has been achieved in the development of materials and techniques which ameliorate these problems, noted examples of which are C.T. Sun's [1989a] controlled damage containment technique; Masters' [1987b], Williams' [1982] and Seferis' [1989] work with interleafing, and a variety of researchers' investigations of through-the-thickness reinforcements. Capturing the efforts of the past 20 years of impact resistance research has resulted in the creation of a user-friendly Hypercard reference database of over 370 papers, articles and monographs which should prove useful as an aid to the designer for improving the impact resistance of a structure. As a result of this literature search, an ever-growing list of impact design heuristics was also compiled, Appendix A. In conjunction with the reference database, this tool provides the designer with a foundation for improving impact resistance in composite structures.

A comprehensive, coherent, and cohesive impact design methodology (Chapter 3), based on the Henshaw and Wilkins [1989] Total Quality Design (TQD) framework, which owes much to the work of Pugh [1981], Hauser [1988], and Clausing [1986], was designed and describes when, where, and how impact design issues are considered in the design process. This flexible methodology requires a focus on the customer's voice throughout the design process, recognizes the dynamical and statistical influence of low-velocity impact threats on the design, insures concurrent integration of impact design criteria with other "design for" considerations, describes an approach for using test and analysis in the design-decision process, and provides for concurrent development for application of specific materials and structural impact resistant solutions.

To support the design-decision process in the impact design methodology a global-local approach to the use of analysis and impact testing was developed which demonstrates how instrumented impact testing and/or static load-deflection testing for local response may be combined with global structural FE modeling and analysis to determine the structure's influence on the impact event. This was accomplished through a number of steps:

> 1) Use of a microcomputer-based FEA of the impact test apparatus to determine its compliance and, thus, its role in the plate bending response, and analysis of plates for Hertzian indentation contribution by Greszczuk [Zukas 1982] and Elber [1983] (Chapter 4)
>
> 2) Identification of the critical few quality metrics, by structural level, for improving and/or assessing the impact resistance of composites and evaluating the ability of a variety of test methods to assess these quality metrics (Chapter 5)
>
> 3) Investigation of two typical carbon fiber reinforced plastic systems for these laminate level quality metrics (Chapter 6)
>
> 4) Use of the data generated to correlate the load-deflection response with static tests and static load-deflection FEA using quasi-isotropic material properties and development of a global-local modeling and testing approach which shows how impact test data can be used directly in design (Chapter 7)

Some specific observations and conclusions of the experimental phase were:

1) The TQD methodology is an effective tool for identifying the critical few response variables for impact resistance and, thus, testing.

2) Low-velocity instrumented impact testing is an effective, efficient, and repeatable method of generating data for direct comparison of the impact resistance (if not strength) of composite materials, provided the user understands the influence of the installation and setup of the test equipment. In particular, identification of the point at which damage initiates—the incipient damage point—is relatively straightforward, giving the designer an elastic design criterion when coupled with the elastic structural compliance as an energy absorbing mechanism.

3) Quantifying the compliance of the impact test fixture was done through the use of FE analysis and insight was gained in terms of its role in the impact event. This FEA suggested a role for the impact tower as a structural surrogate.

3) Static load-deflection test techniques are a cost-effective alternative to instrumented impact tests. Work by Bostaph and Elber [1982] in particular, support this conclusion. However, standardization of these techniques is required. The static load-deflection tests conducted in this study show general agreement with the load-deflection response to incipient damage.

4) For the static and impact tests conducted, carbon/PEEK thermoplastic composites demonstrated an incipient damage energy, Ei, approximately 100% greater than for the equivalent carbon/epoxy system. Other

important criteria (related to E_i)—load to incipient damage, P_i, and deflection at incipient damage, δ_i—likewise demonstrated much greater values in the thermoplastic systems underscoring the inherent toughness of this matrix; however, in all cases these values varied depending on impact energy and structural constraint.

5) Plastic deformation in the thermoplastic system was evident well below the incipient damage point (initiation of matrix cracking, delamination, fiber breakage) suggesting the visual detection of non-critical damage in these systems is more likely than in their carbon/epoxy counterparts. This suggests that an assessment and repair criterion based on visual detection would be adequate for impact damage in these systems.

6) The extensive microcracking and delamination in the carbon/epoxy systems, even at very low energy, suggests that these systems are desirable for use where delamination might be needed as an energy absorbing mechanism to disperse kinetic energy, and delay penetration or fiber breakage.

7) The increase in plate compliance (increase in annular clamping ring size) significantly increased the E_i and δ_i values of both systems for a given impact energy, whereas, P_i remained relatively unchanged. This suggests a significant role for the local Hertzian deformation in generating initial damage in the plate when plate bending is suppressed.

photomicrography are all helpful in gaining an understanding of impact damage modes and damage development processes in composites.

8.3 Future Work

Clearly, the future is ripe with opportunities in the area of improved impact resistant composites. The author believes the following efforts are both achievable and worthwhile for the immediate future in this critical area of composites design:

1) Develop an automated impact design knowledge-based expert system which includes each of the tools identified and/or developed in this study.

2) Integrate the impact design knowledge expert into a comprehensive composites structural design environment which includes "design for" modules for manufacturing, materials selection, joints, processing, cost, etc.

3) Develop fiber/matrix optimization models for impact resistance.

4) Investigate the role of fiber/matrix interfacial bonding on impact properties.

5) Develop FE structural models and compare their load-deflection response experimentally with real structures. Correlate predicted incipient damage points.

6) Investigate use of design of experiment strategies to predict impact response variable dependency.

7) Incorporate in-service thermo-mechanical loads into a predictive impact design test and analysis methodology.

8) Develop, categorize and catalog specific structural stiffener designs and other stress concentrators with respect to their influence on impact properties of composites.

9) Standardize impact test fixtures and installations so that data may be correlated laboratory to laboratory.

10) Develop an application-specific response to design challenges for composites that takes full advantage of the fiber-to-structure flexibility of composites. Force fit solutions are not the answer.

11) Improve field NDE and NDT methods and procedures for detection and assessment of low-velocity impact damage.

12) Develop self-diagnostic composite structures which identify the onset and extent of low-velocity impact damage.

The alacrity with which the speed and power of microcomputers are advancing is astounding. Engineering and scientific analyses which are just imaginable today or possible only on mainframes and supercomputers will be possible at the average engineer's desk top by the turn of century. Image processing, modeling, automatic mesh generation, and nonlinear analysis algorithms needed for sophisticated processing and structural analyses by FE and other techniques are a generation removed

from today's technology. As shown in this thesis, even relatively modest FE capability for today's user-friendly microcomputer platforms can provide insight into structural behavior which was only possible using mainframe computers 10 years ago. All this suggests that these analysis and modeling issues which confound the fundamental understanding of the impact behavior of composites will be problems easily solved in a few years on one's integrated and networked desk top workstation/PC. The ability to take the analytical, heuristic and experimental data of today and integrate it into this interactive design and engineering environment of the near future is an important and exciting challenge, worthy of pursuit by our engineering schools. The author hopes that there is the courage and foresight in the engineering and scientific graduate departments of this nation to accept and promote this design research as a critical and complementary component to traditional reductionist research.

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APPENDIX A
IMPACT DESIGN HEURISTICS

A.1 Purpose

The purpose of this appendix is to provide some basic rules-of-thumb or heuristics for low-velocity impact design. This list is given in a structural hierarchy and is based on the literature survey and experimental work conducted by the author. It is by no means comprehensive, yet it should give the designer some grounding in impact resistant design. These heuristics should be generally applicable for impact events which are < 10 m/sec in velocity and generate < 40 Joules of incident impact energy.

A.2 Constitutive Level Heuristics

For brittle materials the failure under impact would be expected to be governed by the tensile strength and would occur at the periphery of the contact area [Zukas 1982]. For materials with low shear-strength, impact would produce subsurface shear failure [Zukas 1982]. Fiber-Matrix interfacial bonding is crucial to impact damage tolerance and resistance.

A.2.1 Fibers Properties

1) Fiber ultimate strain (ε_{fult}) dominates membrane penetration energy. So, in very thin plates where membrane reaction is dominant over plate flexure or shear deformation, the fiber strain to failure will dominate the composite performance, and matrix properties, no matter how tough, will contribute little to impact resistance [Elber 1985].

2) High-strain fibers offer better impact structural performance than low-strain fibers.[Dow 1988], eg., aramid, nylon, glass, and PE fibers.

3) Impact resistance increases as fiber strength increases and modulus decreases [Zukas 1982].

4) Ultrahigh modulus fibers, eg., Celion GY70 have low impact resistance [Zukas 1982].

5) High strength moderate modulus fibers, eg., Thornel 300, have high impact resistance [Zukas 1982].

6) High strength *and* high ductility fibers such as PE fibers demonstrate good impact resistance as compared with those offering high strength, such as carbon, *or* high ductility, nylon fibers [Jang 1989].

7) At higher velocities and energies penetration resistance of composites appears to be dictated by the fiber toughness [Jang 1989].

High strain-to-failure fibers, such as the aramids and polyethylene, often have poor compressive properties due to high molecular orientation coupled with weak

intermolecular bonding. This is particularly true of the highly oriented Kevlars 49 and 149; therefore, they are best employed for impact resistance on back surfaces (away from the impact) where tensile stress (strain) is high. These fibers, nylon, and glass also have good damping properties relative to carbon fibers so, for high velocity impacts where dynamic effects are of concern these will improve the impact resistance. The tradeoff is usually loss of specific stiffness.

A.2.2 Matrix Properties

1) Excessively strong matrices can result in brittle composites and may result in unsafe failure modes [Elber 1985].

2) Matrix shear strength dominates the damage threshold, particularly in thick laminates [Elber 1985].

3) Matrix toughness normally dominates the type and extent of impact damage [Elber 1985].

4) Matrix materials with higher fracture toughness, K_{1c}, are generally more resistant to impact.

5)"Brittle" resins can provide a "ductile" impact response by higher resin content in the composite, appropriate stacking sequence and fiber orientation.

6) Impact resistance increases as the Young's modulus, E, of the matrix decreases and the strength, σ_{ult} increases [Zukas 1982].

7) To minimize the impact damage, requires that the matrix have high strength and low modulus. (Look out for open hole effects in the concentration of stress in these tough matrices, as the suppression of delamination near the hole may increase the stress concentration and reduce the residual strength [Zukas 1982].)

8) Operating temperature affects the impact resistance of a composite structure due its effect on the matrix in the the range of Tg. For example, the impact energy at room temperature increases by an order of magnitude (to around 70J) for monothane blends between 50% and 65% [Davidson 1985].

9) Fiber and matrix must be matched for strain-to-failure and strength for best impact resistance.

10) As matrix toughness increases damage incipient level, E_i, increases, if failure modes are matrix dominated.

11) As matrix toughness decreases, visual damage detectability decreases.

A.3 Lamina Properties

1) Impact properties improve with increased volume fraction of matrix material.

2) Impact properties improve with increased and controlled fiber spacing in the matrix [DeRosset 1975].

3) In-plane tensile stresses and interlaminar shear stresses are dominant factors causing initial matrix crack, therefore $\varepsilon_{90°}$ is critical.[Chang 1990].

4) Interlaminar shear stresses cause delamination, mode II interlaminar fracture [Maikuma 1990, Chang 1990]; therefore, improving interlaminar shear strength and increasing mode II strain energy release rate, G_{IIc}, enhance damage tolerance to low-velocity impacts.

5) Delamination is initiated by the "critical" matrix cracks [Chang 1990]; therefore, delay matrix cracking (by higher matrix toughness, higher resin content, higher interlaminar shear strength) to prevent life limiting delamination.

6) Delamination *growth* is dominated by suddenly increased out-of-plane normal stresses (Mode I fracture) as a result of matrix cracking [Chang 1990]; therefore, improve G_{Ic} to delay delamination growth. (Note this is beyond incipient damage point, so damage tolerance is the issue here.)

7) Thermal residual stresses have a significant affect on matrix cracking [Chang 1990]; as residual stresses decrease, impact resistance increases and durability increases.

8) Delay or prevent transverse *intralaminar* microcracking to improve durability and damage tolerance.

9) Both fiber and matrix properties must be improved and matched for best impact resistance.

10) The fiber/matrix interface is a stress concentrator and site for propagation of matrix cracking, particularly in resin poor regions. Improving the interfacial strength and increasing resin content between adjacent fibers improves impact resistance.

A.4 Laminate Properties

Many of the general rules applying to lamina apply equally at the laminate level.

1) Delay or prevent transverse intralaminar and *interlaminar* microcracking to improve durability and damage tolerance.

2) In-plane tensile stresses are the dominating factor causing initial matrix cracking, therefore, the 90° critical strain value is crucial to the inherent impact resistance (durability) of the composite.

3) Delay or prevent interlaminar delamination to improve damage tolerance.

4) Interlaminar shear stresses cause delamination and delamination is initiated by "critical" matrix cracks. Delamination growth is dominated by suddenly increased out-of-plane normal stresses (Mode I fracture) as a result of matrix cracking.

5) Plastic deformation contributes to high interlaminar fracture toughness improving impact resistance [Dorey 1985].

6) Threshold energies exist above which impact damage occurs.

7) Thermal residual stresses are critical, having significant affect on matrix cracking.

8) Interlayers can be used to either promote energy-absorbing delamination failure (by use of a perforated plastic film) for ballistic protection (anti-penetration) application or as a means of preventing or delaying delamination (eg. using toughened interlayers) for damage tolerance or durability. These approaches are opposite sides of the coin of "controlled interlaminar bonding" [Jang 1989].

A.4.1 Fiber Orientation

1) Damage zone is minimized if the layers are dispersed through-the-thickness and the fibers are placed in a bidirectional layup [Zukas 1982].

2) Lay-ups in order of best impact resistance [Zukas 1982].

a) 1:1 bidirectional

b) tridirectional

c) 2:1 bidirectional

d) unidirectional

3) ±45° laminates offer damage containment, i.e., they are damage tolerant techniques [Rogers 1989a].

4) Separate laminates of all ±45° plies for shear strength [Rogers 1989a].

A.4.2 Stacking Sequence

1) 0° plies should not be greater than 60% of angle plies in a layup.

2) 0° plies should be interspersed with not more than two plies of any orientation together.

A.4.3 Laminate Thickness

1) Failure for thin plates (up to 32 plies) is determined by plate bending stresses (failure occurs at the back surface), Greszczuk [Zukas 1982].

2) For very thin plates (or large distances between stiffeners) where deformation exceeds 1.5 to 2 times the plate thickness, membrane action is dominant and fiber strength controls the failure mode [Bostaph 1982].

3) With increasing thickness (or suppression of bending due to stiffeners, etc.. plate bending stresses become smaller and damage is from local contact stresses (compressive stress under the impactor, tensile stresses on the periphery of the contact zone, or subsurface shear stress) Greszczuk [Zukas 1982].

4) Thicker laminates have higher incipient damage points than thinner laminates, given equivalent structural constraints.

A.4.4 Sublaminate Thickness

1) Complete dispersion of the layers through-the-thickness is more resistant to damage than if the layers are not dispersed, i.e., reducing

effective ply thickness increases impact resistance, Greszczuk [Zukas 1982].

2) Delamination is the most prevalent life-limiting failure mode in composites. For damage tolerance and durability it should be suppressed. (Be careful around open holes and in the case where loads are monotonically tensile.) Mode I strength can be used to determine the delamination resistance of the composite.

3) Interleafing delays the onset and growth of delamination damage in low-velocity impact for a given impact energy in graphite/epoxy composites, i.e., increases G_{IIc} values. High interlaminar shear strain values are desirable for improved impact resistance.

4) Maximum resin content and thinner plies/ply group will give a high resistance to microcracking.

A.4.5 Hybrids

1) Polyethylene, PET, and nylon fibers have been shown to absorb large amounts of energy prior to failure.

2) Place fibers in a laminate sequence to maximize its ability to improve impact resistance. For example, use aramid fibers on the back surface where tensile stresses are high.

A.5 Structural Level

The incident energy of the impactor may be absorbed, dissipated and/or accommodated by the energy of bending (flexure of the structure), energy to compress the structure, energy of local deformation (created by contact forces), energy of elastic deformation of the structure, energy to create damage—matrix dominated: matrix cracking, delamination, plastic deformation of the matrix; fiber dominated: fiber buckling, fiber breakage, plastic deformation of the fibers (eg. PE, KEVLAR), fiber pullout, fiber-matrix debonding.

1) Take a global view of impact [Sjoblom 1987]. Impact is a systems level problem, not a local one [Cairns 1987].

2) Delay or prevent transverse intralaminar and interlaminar microcracking to improve durability and damage tolerance.

3) Relatively low-velocity bending can occur and no damage results if the energy of impact can be accommodated by the elastic strain energy of the laminate and the structure. The critical condition exists when local stress exceeds local strength [Dorey 1984].

4) Target configuration and constraints are vitally important in the impact response.

A.5.1 Through-The-Thickness Reinforcements

1) Braided or woven carbon fiber-epoxy composites are not as sensitive

as the unidirectional prepreg laminates, when subjected to low velocity impact, in terms of reduction compressive properties [Fang 1988].

2) To minimize the interlaminar stresses (delay onset and growth of delamination) improve structural configurations such as discrete stiffness design, use stitching, tough resin systems and/or hybrids [Garg 1988].

3) Braids have similar strength and elastic properties to corresponding angle-plied laminates while greatly limiting the extent of impact damage. The braid does not increase the impact damage threshold, however [Gause 1987].

4) 3-D reinforcements result in smaller damage area with little or no delamination compared to 2-D composites. The failure process in 3-D composites proceeds gradually [Jang 1989].

5) Stitching through a prepreg may cause reduction in in-plane properties and flexural strength due to fiber damage but improves impact strength by arresting cracks and delaminations and improving z direction compressive strength.

6) Stitched Z-direction Kevlar fibers are effective in arresting delamination propagation.[Jang 1989].

7) Stitching thermoplastic preforms has a smaller positive effect on out-of-plane mechanical properties compared with thermosets due to their general higher matrix toughness.

A.5.2 Stiffeners, Spars, Ribs, Joints, Fasteners

1) The critical impact damage location in a structure depends on the structural configuration and substructural member arrangement [Demuts 1989].

2) Built-up configuration of the panels, multispar and multirib wing designs, provides a significant increase in impact damage tolerance coupons [Demuts 1985].

3) Avoid design features that cause stress concentration:

a) free edges (generated in sublaminates where microcracking has occurred interlaminarly)

b) ply drops

c) joints

d) fasteners (These can sometimes act as through-the-thickness reinforcement and suppress delamination, acting as crack stoppers.)

d) Structural stiffeners are concentrators. Impact damage occurs at lower energy levels.

A.5.3 Plate Geometries

Target curvature affects both the magnitude and distribution of surface pressure caused by the impact as well as the shape of the area of contact: (1) area of contact is elliptical and approaches a circle as the radius of the cylinder increases, (2) the area of contact decreases with decreasing cylinder radius, (3) maximum load resulting from impact, decreases with decreasing cylinder radius, (4) maximum surface pressure increases with decreasing cylinder radius, and (5) contact duration increases with decreasing cylinder radius. These effects will in turn affect the mode and extent of

failure. Cylinder boundary conditions will also influence the impact parameters and failure modes, Greszczuk [Zukas 1982].

A.5.4 Sandwich Panels

1) Impact energy absorbed by a composite sandwich containing single-layer facesheets increases many-fold compared to that of the foam core when alone.

2) Impact response of sandwich panels is controlled by the facesheets if facesheet material is tough enough. (eg. containing PET or high strength PE fibers) [Jang 1989].

3) Impact failure mechanisms of panels with carbon fibers are foam core dominated [Jang 1989].

APPENDIX B

TQD IMPACT DESIGN METHODOLOGY

In this appendix, the Excel TQD spreadsheets used to identify the customers' wants and quality metrics for the Impact Design Methodology are shown. The real power of these TQD tools is the ability to work through them interactively at the computer terminal In order, the output presented is the customer and customer wants (CW's) list; the House of Quality, where correlations between CW's and QM's are made; and the critical few QM's which used to evaluate the methodology against competing methodologies in the Pugh Concept Selection Process.

Table B.1 IDM Mission Statement, Customer List and CW's

Mission Statement

Develop a methodology for optimizing composite structures designs for impact resistance and show how impact test results can be used in design.

Top Customer Wants	Relative Importance
1 Comprehensive and coherent Impact Design Methodology (IDM)	5
2 Use impact test data for design	5
3 Impact design criteria	5
4 Std. test design meth./strategy	5
5 Easy to use CAD/CAE Impact Design Tools	4
6 Understanding influence of the test fixture on the impact response	4
7 Inexpensive test method	4
8 Impact design heuristics	3
9 Impact resistance techniques	2
10 Understand/predict impact phenomenon	2

Top Customers		Relative Importance
1 CCM Consortium members-Industry and Government		5
2 End-User(OEM)	Aerospace	5
	Defense	5
3 DOD Labs/RD&E centers		5
4 CCM Staff and Faculty		4
5 PM shops	LHX	4
	Blackhawk	4
6 CCM Students		3
7 PM shops	CIFV	3
2 End-User(OEM)	Automotive	2

Table B.2 IDM House of Quality for Evaluating and Correlating the CW's with QM's

Mission Statement: Develop a methodology for optimizing composite structure designs for impact resistance. Show how impact test results can be used in design.

CUSTOMER WANTS

- Comprehensive and coherent Impact Design Methodology (IC
- Use impact test data for design
- Impact design criteria
- Std. test design meth./strategy
- Easy to use CAD/CAE Impact Desi
- Understanding of the influer
- Inexpensive test metl

	Comp	Use i	Impac	Std. t	Easy t	Under	Inexp	TOTALS
Rate of Importance	5	5	4	3	2	4	5	
Current Performance	3	2	2	2	2	1	2	
Top Competitors								
Building Block Approach	4	2	2	2	2	1	1	
Sjoblom's Global View of Low-Velocity Impact	4	2	2	2	2	1	2	
Tsai's Composites Design	2	2	2	1	3	1	1	
Nolet's A-10 Wing Leading edge	3	3	2	2	3	1	2	
Grumman F-111 Leading edge for horizontal stab.	4	3	2	2	2	1	1	
C-130 Thermoplastic belly skin	4	2	2	2	3	1	2	
(TQD) Total Quality Design	5	2	3	3	4	3	3	
Planned Performance	5	4	5	4	5	4	4	
Ratio of Improvement	1.7	2.0	2.5	2.0	2.5	4.0	2.0	
Leverage (1=low, 1.5=high)	2	2	1	1	1	2	2	9
Absolute Weight	12.5	15.0	12.0	6.6	5.0	24.0	15.0	90
Demand Weight	13.9	16.6	13.3	7.3	5.5	26.6	16.6	100

IMPACT DESIGN METHODOLOGY QUALITY METRICS	Comp	Use i	Impac	Std. t	Easy t	Under	Inexp	Points	%
Repeat use of methodology by design teams	◆◆	◆◆	◆	◆	◆	◆◆	◆◆	795	7.4
Cost to design structure	◆◆	◆◆	◆◆	◆◆	◆◆	◆	◆◆	793	7.4
Impact testing costs—component	◆◆	◆◆	◆◆	◆	=	◆◆	◆	760	7.1
Time to design structure for impact resistance	◆◆	◆◆	◆	◆◆	◆	◆◆	◆	758	7.0
# Industries using the methodology	◆◆	◆◆	◆	◆	◆	◆◆	=	662	6.2
# Companies using the methodolcgy	◆◆	◆◆	◆	◆	◆	◆◆	=	662	6.2
Impact testing costs—coupon	◆	◆◆	◆◆	◆		◆	◆◆	659	6.1
# new effect. impact tech. developed/# dcsigns	◆◆	◆◆	◆◆	◆	◆	=	◆◆	635	5.9
Impact testing costs—structure	◆◆	◆◆	◆	◆	◆	◆	◆	622	5.8
Impact testing costs—subcomponent	◆	◆◆	◆◆	◆	=	◆	◆	598	5.6
Acceptance by design team (technical and manageme	◆	◆	◆	◆◆	◆	◆	◆◆	596	5.5
# of impact tests eliminated (product specific)	◆	◆◆	=	=	=	◆	◆◆	528	4.9
Reduction in Life-cycle cost for impact vulnerable s	◆◆	◆◆	=	◆	◆	◆	=	502	4.7
Modeling costs	◆	=	=	◆	◆◆	◆◆		426	4.0
Life-cycle repair costs	◆◆	◆◆	◆	=	◆	=	=	420	3.9
Life-cycle maintenance/inspection costs	◆◆	◆◆	◆	=	◆	=	=	420	3.9
# citations of use of the methodology in literature	◆◆	◆◆	=	=	=	=	◆	411	3.8
Methodology training costs/time	=	=	=	◆	◆		◆	191	1.8
Methodology software costs/time to design	◆◆	=	=	=	=			168	1.6
Accuracy of models (predictive capability)	◆	=	=	=	◆◆			157	[illegible]

Table B.3 Impact Design Methodology House of Quality Correlations

IMPACT DESIGN METHODOLOGY QUALITY METRICS	Competitors Values								
	Building	Sjoblom'	Tsai's C	Noiet's A	Grumma	C-130 T	(TOD) T	NOW	PLAN
Repeat use of methodology by design	2	2	1	3	2	4	5	4	5
Cost to design structure	1	2	2	3	2	4	5	4	5
Impact testing costs—component	?	?	5	?	?	?	5	4	5
Time to design structure for impact	5	4	4	?	5	5	4	2	5
# Industries using the methodology	4	?	4	4	4	4	4	3	4
# Companies using the methodology	4	?	3	3	3	4	4	3	4
Impact testing costs—coupon	3	?	?	2	2	3	5	3	5
# new effect. impact tech. develope	1	?	?	1	1	3	5	3	5
Impact testing costs—structure	4	3	2	3	4	4	3	4	5
Impact testing costs—subcomponent	5	?	?	?	?	?	?	2	5
Acceptance by design team (technica	5	?	3	3	3	?	2	1	3
# of impact tests eliminated (produ	2	?	4	4	4	?	5	3	4
Reduction in Life-cycle cost for im	1	3	3	3	1	2	3	2	4
Modeling costs	4	1	1	1	2	2	?	1	5
Life-cycle repair costs	3	?	?	4	4	4	4	?	5
Life-cycle maintenance/inspection	4	?	?	4	4	4	4	?	5
# citations of use of the methodolo	2	?	4	3	2	?	4	?	4
Methodology training costs/time	4	2	3	2	4	3	4	2	5
Methodology software costs/time to	4	2	3	2	4	3	4	2	5
Accuracy of models (predictive cap	?	?	?	2	2	2	?	1	5
% of FE modeling done in the early d	2	?	?	3	?	?	?	1	4

Ranking Notation

5	Very High	Very Good	Always Exceeds Performance Obj.
4	High	Good	Usually Exceeds Performance Obj.
3	Average	Average	Meets Performance Obj.
2	Low	Bad	Sometimes fails to meet Performance Ob
1	Very Low	Very Bad	Always fails to meet performance Obj.
?	Unknown		

Table B.4 Impact Design Methodology Pugh Concept Selection Process

Mission Statement:

Develop a methodology for optimizing composite structures designs for resistance. Show how impact test results can be used in design.1990.

	Concept Descriptions
Benchmark	Building Block Approach
1	Sjoblom's Global View of Low-Velocity Impact
2	Tsai's Composites Design
3	Nolet's A-10 Wing Leading edge
4	Grumman F-111 Leading edge for horizontal stab.
5	C-130 Thermoplastic belly skin
6	(TQD) Total Quality Design

Quality Measures	Concepts							
		1	2	3	4	5	6	7
	B							
QUALITY METRICS	e							
Time to design structure for impact resistance	n	s	?	s	-	s	+	
Cost to design structure	c	s	?	s	s	s	+	
Methodology training costs/time	h	?	+	s	s	s	+	
Acceptance by design team (technical and managemen	m	s	s	s	s	s	s	
Impact testing costs—coupon	a	s	+	s	s	s	+	
Impact testing costs—subcomponent	r	s	s	?	?	s	+	
Impact testing costs—component	k	s	s	?	?	s	+	
Impact testing costs—structure		s	s	?	?	s	+	
Reduction in Life-cycle cost for impact vulnerable structure			+	s	s	s	s	
Repeat use of methodology by design teams	B	?	+	s	s	s	+	
Modeling costs	e	?	s	s	s	s	+	
Accuracy of models (predictive capability)	n	?	?	s	s	s	+	
# of impact tests eliminated (product specific)	c	?	?	s	s	s	+	
# citations of use of the methodology in literature	h	?	?	s	s	s	-	
Life-cycle repair costs	m	s	?	s	s	s	s	
Life-cycle maintenance/inspection costs	a	s	?	s	s	s	s	
Methodology software costs/time to design	r	s	+	s	s	s	+	
# Industries using the methodology	k	-	-	s	s	s	-	
# Companies using the methodology		-	-	s	s	s	-	
# new effect. impact tech. developed/# designs	B	s	?	s	s	s	+	
	e							
	n							
Number positive attributes	c		5				13	
Number negative attributes	h	2	2		1		3	
Number equivalent measures	m	11	5	17	16	20	4	
Number knowledge gaps	a	6	8	3	3			

APPENDIX C

IDM PROJECT PLANNING TEMPLATES

This appendix shows the PERT (CPM) MacProject II planning templates for design team product development planning. The impact-design inputs and outputs are indicated for each phase in the project planning process. The electronic version of the template is easily tailorable for the project at hand. Training is self-paced and requires 1 to 2 hours to gain rudimentary proficiency with the software. The reader is advised to use the templates in conjunction with the Impact Design Methodology discussions of Chapter 3.

Impact Design Project Planning Template
Phase I — Getting Started

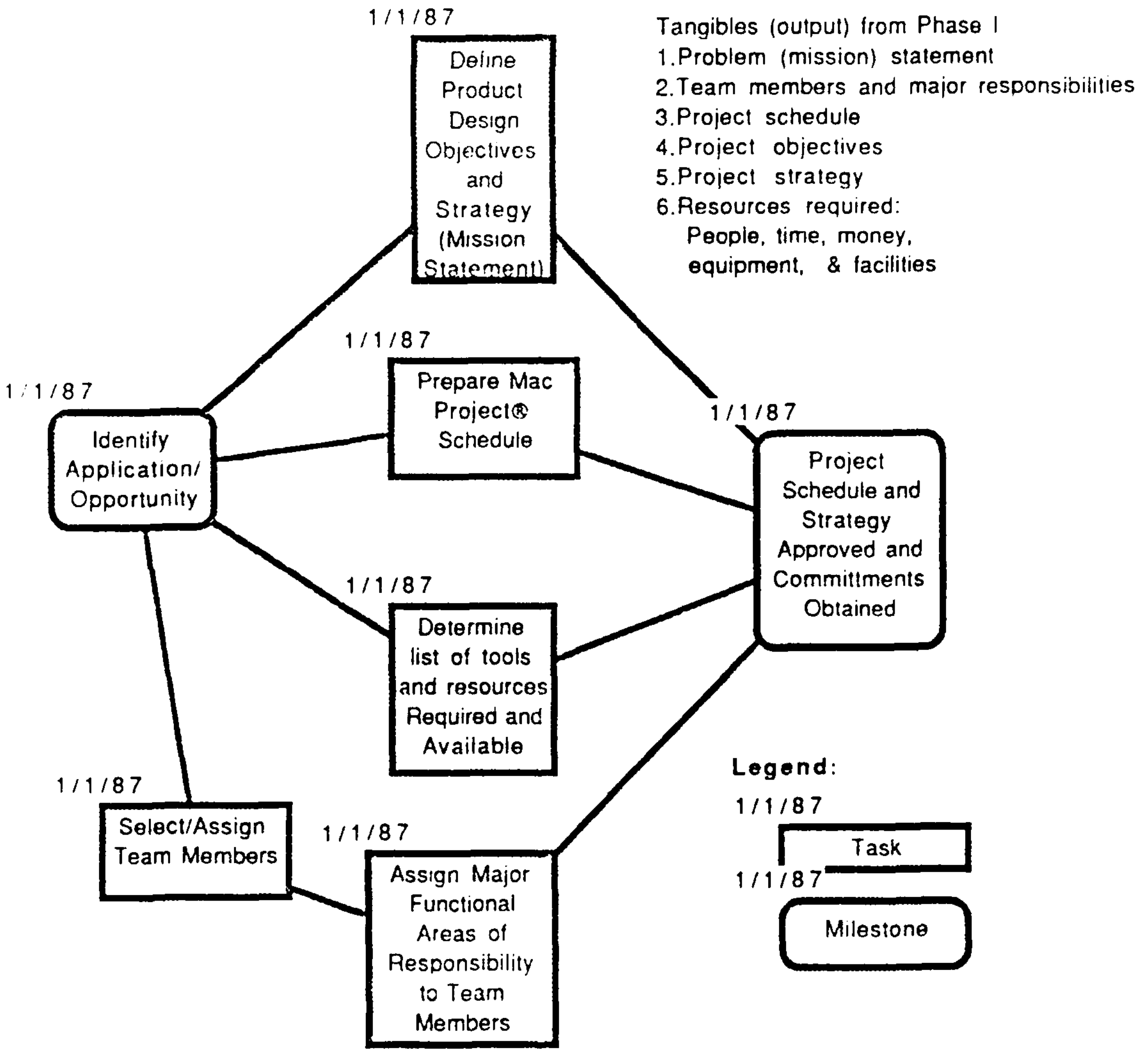


Figure C.1 Phase I Getting Started uses elements from the TQD framework.

Impact Design Project Planning Template
Phase II—Assessing the Opportunities—House of Quality

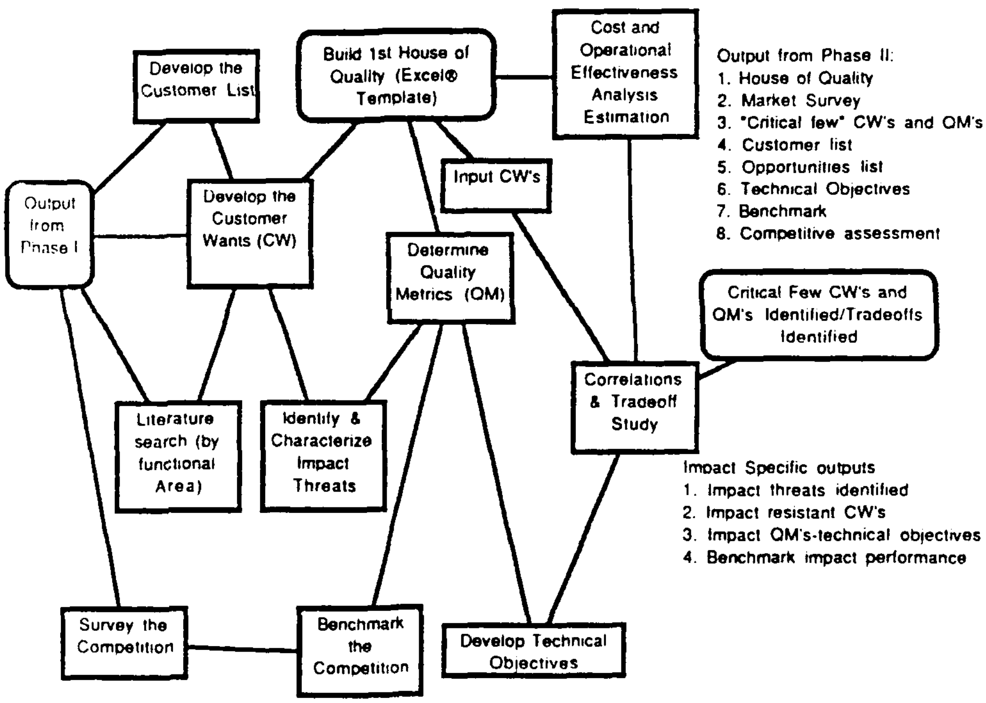


Figure C.2 Phase II Assessing the Opportunities—House of Quality

Impact Design Project Planning Template

Phase III—Concept Development-Pugh Concept Selection

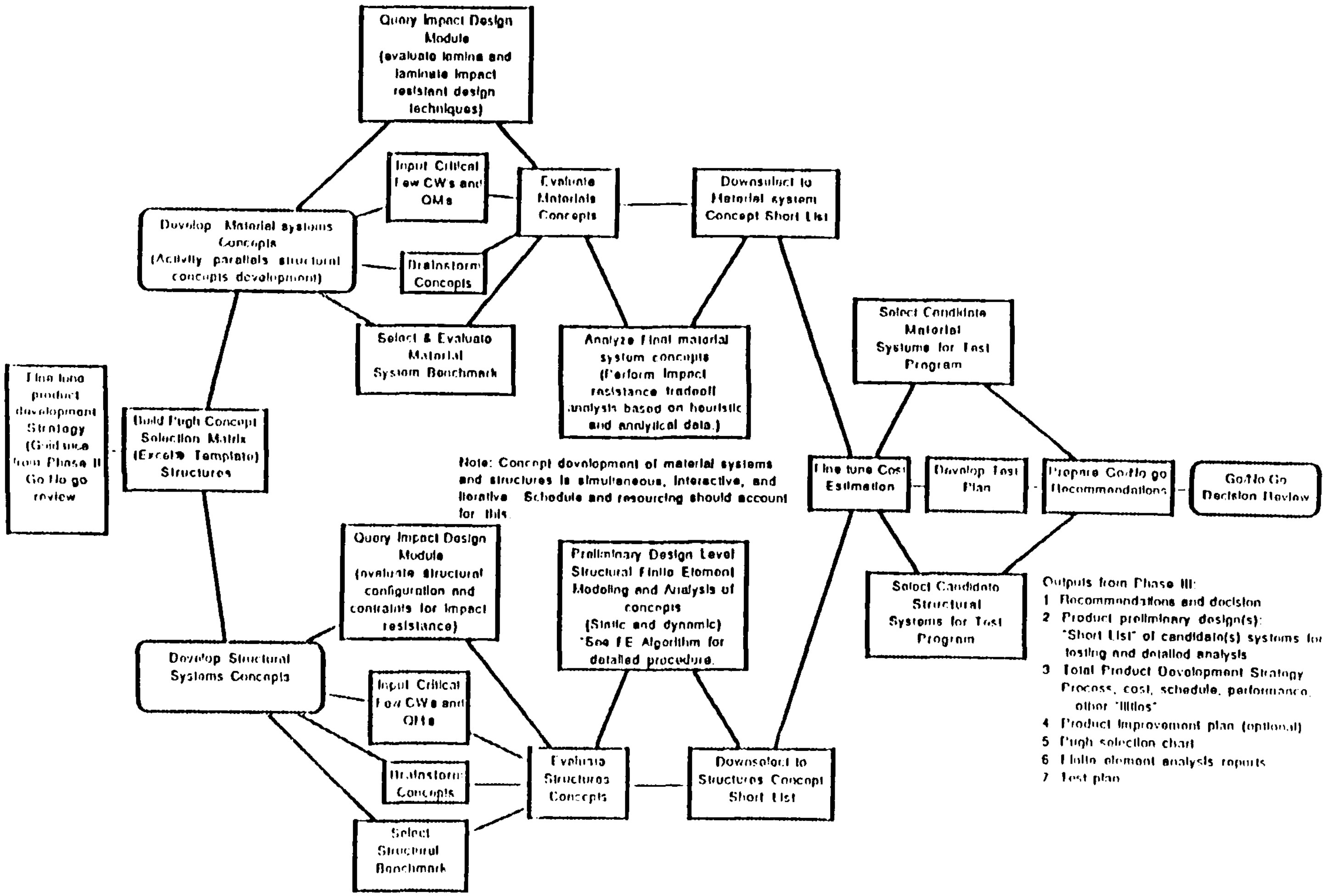
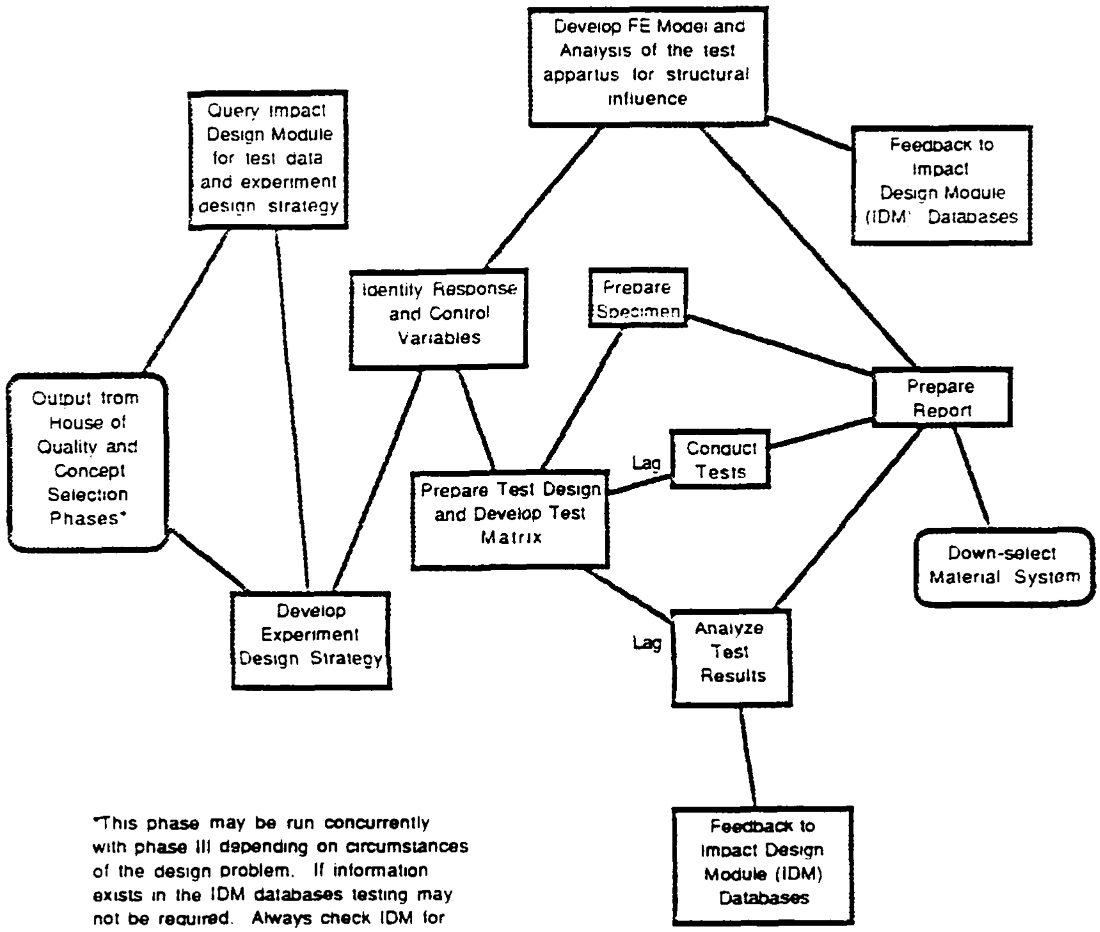


Figure C.3 Phase III Concept Development—Pugh Concept Selection. (Concurrency of the materials selection and structural development is evident in this template.)

Impact Design Project Planning Template

Phase IV—"Design for Impact" Test Plan

Sub-phases 0 and 1— Coupon Tests



*This phase may be run concurrently with phase III depending on circumstances of the design problem. If information exists in the IDM databases testing may not be required. Always check IDM for data before proceding with testing.

Output from Sub-phases 0 and 1:
1. Experiment design strategy and objectives
2. List of impact response and control variables
3. Test schedule
4. Experimental results and conclusions
5. Data feedback to Impact Design Module
6. FE model of test apparatus
7. Most promising materials list with tradeoff analysis

Figure C.4 Phase IV "Design for Impact" Test Plan. (Sub-phases for each structural level of assessment are included and are tailored to the particular project.)

APPENDIX D

FINITE ELEMENT GUIDELINES

D.1 Purpose

This appendix is intended to be used as a general reference guide for planning, evaluating, and reporting finite element modeling and analysis. The Macintosh-based FEA software used in this study is a user-friendly menu driven FE tool which the author found enhanced his capability to understand as well as analyze his structural mechanical problems involving static analysis of the impact test fixture (isotropic properties).[1]

D.2 The Finite Element Method

The aims of the finite element analysis include [MSC 1989]:

1) Gaining insight into structural behavior.

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[1] Analysis of problems involving fully anisotropic properties can be done on the Macintosh using COSMOS™/M, Structural Research and Analysis Corporation, a FE modeler/analysis package However, because of the increas ‹› ‿omputational intensity of problems of this type a high speed microprocessor, such as that available with the Macintosh IIfx, is recommended by the author.

2) Assessing structural integrity—whether the structure will fail under the applied load, or how much reserve strength is inherent in the design.

3) Assessing structural behavior changes due to design modifications.

4) Simulating or helping to interpret the results from structural testing.

D.3 Steps in a Finite Element Analysis

The following list is from Table 1.1 [Baran 1988]:

1) User creates the finite element model. *Discretization rule-of-thumb:* the more node points, the more accurate the solution. But what is the trade-off? Time.

a) Define geometry, nodes and elements.

b) Specify material properties, loading conditions, and boundary conditions.

2) Finite element program performs analysis.

a) Formulate equations.

b) Solve equations.

3) Finite element program reports results.

a) Compute node and element values (displacements, temperatures, stresses, reaction forces, etc.).

b) Post-process results (plots, code checks, etc.).

The following is required for analysis:

1) Nodal Point Spatial Locations.

2) Structural elements that connect the nodal points, representing the stiffness of the structure.

3) Mass properties of the structure.

4) Boundary conditions or structural restraints.

5) Static and dynamic load specification.

D.4 FE Modeling Techniques

D.4.1 General Modeling Considerations

These modeling tips are gleaned from Baran [1988] and from the author's practical experience with LAPCAD and MSC•PAL2:

1) Models are an idealization of the real structure. Remember, in real life there are no such things as point loads, lumped mass, or plane strain. Boundary conditions are never really quite as simple as fixed or simply supported.

2) Effective and thoughtful modeling, however, will give what Baran terms "reasonably accurate results."

3) *Trade off* between accuracy and computational efficiency.

4) Primary "rule-of-thumb" for modeling, "Start off with a *simple model*."

5) Most problems can be handled with simple beams, plates, and solid elements.

6) Solve in *two-dimensions* whenever possible.

7) Use *simplifying assumptions*: plane stress and plane strain to reduce the size and complexity of the model.

8) Take advantage of *symmetry* where appropriate to simplify the problem (symmetry in geometry, loads and boundary conditions).

9) There is no cookbook solution to FE Modeling and Analysis.

D.4.2 Designing the Mesh

The most critical part of the finite element model is the "discretization" step:

1) Define the overall geometry, loads and supports.

2) Select the element type(s).

3) Define the nodes and elements.

4) Define the geometric and material properties.

5) Apply the loads and boundary conditions.

D.4.3 Some More Helpful Rules for Finite Element Modeling

Again, these rules-of-thumb are largely attributable to Baran [1988].

1) Apply St. Venant's principle to determine minimum dimensions and areas requiring a refined mesh. (Use problems involving concentrated loads and/or geometric discontinuities.)

2) Use a more refined mesh for stress analysis than displacement analysis.

3) Perform convergence study for 2) above, if necessary.

4) Where practical, use uniform mesh pattern (equal node spacing).

5) At transitions—course to fine mesh—do not change the dimensions of adjacent elements by more than a factor of 2.

6) When using plate or axisymmetric elements, use quadrilateral plate elements whenever possible.

7) Use triangular elements only for transitions or when required by geometry.

8) Aspect ratio (length to width) for triangular and quadrilateral elements should be close to 1.0. Up to 5.0 is permissible but keep lower than 3.0 if possible.[1]

---

[1]MSC•PAL2 warns the user when elements in a model violate the suggested aspect ratios.

9) Triangle and quadrilateral elements should not have extremely acute or obtuse angles. Deviations of up to 30° from the optimum equilateral angle in triangular elements and the right angle in quadrilateral elements are permissible.

10) Curved surfaces may be modeled with flat elements if the angle subtended does not exceed 15°. Plate elements should not be warped.

11) Poisson's ratio should be below 0.5. For materials approaching Poisson's ratio of 0.5, special elements are required.

12) Lengths and areas of line (beam) and areas (plate, solid) of elements must be nonzero.

13) Elements should not extend across discontinuities or thickness changes. Add additional nodes and use more small elements in these cases.

14) Flat plate elements have no in-plane rotational stiffness. In order to model flat plates subjected to in-plane torsion, it is necessary to constrain the in-plane rotational degrees of freedom.

D.5 Reporting Finite Element Analysis Result

Thorough documentation of any finite element analysis is essential for making engineering or design decisions [Baran 1988].

A FEA report should contain the following:

1) Description of the objectives of the analysis. Describe the failure criteria or engineering requirements against which the analysis will be compared.

2) Physical description of the part to be analyzed. The overall dimensions, material, loading conditions, and description of the operation or application of the part should be included. Graphic presentation is best.

3) Brief summary of the FE program and computer system used (optional).

4) Plot of the finite element model and description of types of elements used, boundary conditions, applied loads and relevant engineering assumptions.

5) Displacement, mode shape, thermal and/or stress contour plots. A discussion should accompany these plots, describing the behavior of the model and how it relates to the actual expected behavior of the part.

6) Table showing the stresses and displacements for critical sections of the model. Complete output is generally attached as an appendix to the report.

7) Hand calculations supporting the finite element results. A brief discussion of these calculations along with references should be included. This may also be included as an appendix.

8) Conclusions and recommendations. Describe what was learned from the analysis and what conclusions can be drawn. Summarize the results in conjunction with failure criteria or engineering requirements. If the analysis shows an inadequate design, recommendations for design modifications would be included in this section.

APPENDIX E

TQD IMPACT RESISTANCE CRITERIA

Excel TQD spreadsheets, to identify the customers' wants and quality metrics for impact resistance criteria, or developing impact design solution and test plans, are presented in this appendix. A Pugh Concept Selection process template is given for use in evaluating materials and structural concept for impact resistance.

Table E.1 Mission Statement, Customer List and CW's

Mission Statement:

Identify critical few impact test and design criteria for each structural level for inclusion in a global impact design methodology.

Top Customer Wants	Rate of Importance
1 Delay Microcracking	5
2 Superior Damage Tolerance (Safe function in presence of impact damage	5
3 Prevent or Control Delaminations	5
4 Predictable Impact Performance	5
5 Linear elastic failure criterion	4
6 Superior Durability (withstand impact)	4
7 Simple impact test method generates design data	4
8 Impact damage modeling capability	3
9 Reduce impact damage contribution to LCC	3
10 Ease of Damage Detectability (field detection)	3

Top Customers	Rate of Importance
CCM Consortium members-Industry and Government	5
End Aerospace design engineers	5
Defense industry design engineers	5
DOD Labs/RD&E centers	5
PM LHX	5
Automotive Industry	4
CIFV	4
Blackhawk	4
CCM Staff and Faculty	3
CCM Students	2

Rate of Importance

5- Very High
4-High
3-Average
2-Low
1-Very low

Table E.2 House of Quality for Evaluating and Correlating the CW's with QM's

Mission Statement: Identify critical few impact test and design criteria for each structural level for inclusion in a global impact design methodology.

CUSTOMER WANTS

- Delay Microcracking
- Superior Damage Tolerance (Safe function in pres
- Prevent or Control Delaminations
- Predictable Impact Performance
- Linear elastic failure criterion
- Superior Durability (withs'
- Simple impact test

	Delay	Super	Preve	Predi	Linea	Super	Simpl	TOTALS
Rate of Importance	5	5	5	5	4	4	4	
Current Performance	3	3	3	2	3	2	1	
Top Competitors								
Planned Performance	4	4	4	4	4	3	4	
Ratio of Improvement	1.33	1.33	1.33	2	1.33	1.5	4	
Leverage (1=low, 1.5=high)	1	1	1	2	1	1	2	9
Absolute Weight	8.7	8.7	8.7	15.0	7.5	6.6	24.0	79
Demand Weight	11.0	11.0	11.0	19.0	9.4	8.3	30.4	100

Table E.3 Impact Resistance Criteria House of Quality Correlations

Impact Resistance Metrics									
QUALITY METRICS	Delay	Super	Preve	Predic	Linea	Super	Simpl	Points	%
Lamina and constitutive properties									
90° critical strain-lamina	++	++	++	+	++	++	+	703	5.1
ratio of fiber to matrix CTE	++	++	+	?		+	?	540	3.9
fiber/matrix interfacial shear strength	++	++	++	?	?	+		480	3.5
Young's modulus of matrix	++	++	=	=	++	++		387	2.8
matrix strain to failure	++	++	=	=	++	++		387	2.8
fracture toughness of matrix	++	+	+	=	++	+	=	384	2.8
% matrix crystallinity & size of crystals	++	+	=	?	?	++		382	2.7
Shear modulus of matrix	=	+	++	+	+	+		348	2.5
damping properties of fiber	?	+	++	+		+		345	2.5
fiber strain to failure	=	+	+	?	+	++		338	2.4
modulus of fiber	=	+	+	=	?	++		262	1.9
lamina dynamic fracture toughness	=	+	++	=		=		192	1.4
Laminate									
Damage Initiation Energy, Ei	++	+	++	++	++	++	++	856	6.2
90° critical strain-laminate	++	+	++	++	++	++	+	735	5.3
Damage Propagation Energy, Ep	+	++	++	?	?	+	++	709	5.1
Area damage zone size	++	++	++	+	?	+	+	632	4.5
Nonvisible damage area	++	++	++	+	?	+	+	632	4.5
Deflection at max. load, dm	+	++	++	+	++	+	+	625	4.5
Deflection at critical matrix cracking, dc	++	+	+	++	++	++	=	569	4.1
Strain energy release rate, GIC	=	++	++	+	+	+	+	544	3.9
Maximum Energy Absorption, Em	+	++	++	+		+	+	540	3.9
"effective ply thickness"	=	++	++	+		++	+	530	3.8
Strain energy release rate, GIIC	=	++	++	+	+	=	+	510	3.7
interlaminar shear strength	=	++	++	+		+	+	497	3.6
Volumetric damage zone size (C-Scan)	++	++	++	+	?	+		480	3.5
Quadratic Delamination Criterion (QDC)	=	=	++	+	++	=	+	461	3.3
Total Energy Absorption (loss), Et	=	++	++	=		+	+	421	3.0
strain rate to critical matrix cracking	++	+	+	?	?	+		392	2.8
Tensile After Impact Strength	=	++	=	?	?	=		271	2.0
Ductility Index	+	+	=	?	?	=		271	2.0
Contact damage zone-Visual, cm2	=	+	+	=		+		181	1.3
# of impacts to critical matrix cracking	=	+	+	=		+		181	1.3
Compression After Impact Strength	=	+	+			=		129	.9
Structure									
Load to damage initiation, Pi	++	+	++	++	++	++	++	856	6.2
Load to damage propagation, Pp	+	++	++	?	?	+	++	709	5.1
Location of impact relative to stress concentrators (	++	++	++	+	+	++	=	544	3.9
compliance of structure	+	++	++	+	+	++	=	500	3.6
Configuration of stiffeners	+	++	++	+	=	++		432	3.1
Distance between stiffeners	++	=	++			+	+	402	2.9
bending of structure	++	++	++	=	=	+	=	396	2.9
vibration of strucure	?	++	+	?	?	+		392	2.8
frictional energy loss, Ef	?	+	+	?	?	+		348	2.5
detectability of damage		++		+				194	1.4
Local compressive properties	+	+	=			+		162	1.2

Note: Criteria are organized by structural level—constitutive to structural. The values in the "%" column represent the relative importance of the QM's. The user may elect to use as many or as few of the QM's in his concept evaluation as desired.

Table E.4 Impact Resistance Criteria Pugh Concept Selection Process Template

Impact Resistance Concepts Template	Concept Descriptions
Benchmark	
1	
2	
3	
4	
5	
6	
7	

		Concepts						
Critical Few Quality Metrics—Lamina/Laminate		1	2	3	4	5	6	7
	B							
QUALITY METRICS	e							
Lamina and constitutive properties	n							
Young's modulus of matrix	c							
Shear modulus of matrix	h							
matrix strain to failure	m							
fiber strain to failure	a							
GIC toughness	r							
% matrix crystallinity & size of crystals	k							
modulus of fiber								
lamina dynamic fracture toughness								
fiber/matrix interfacial shear strength	B							
90° critical strain-lamina	e							
fracture toughness of matrix	n							
damping properties of fiber	c							
GIIC Toughness	h							
ratio of fiber to matrix CTE	m							
Laminate	a							
90° critical strain-laminate	r							
effective "ply" thickness	k							
interlaminar shear strength								
Compression After Impact Strength	B							
Area damage zone size	e							
Tensile After Impact Strength	n							
Damage Initiation Energy, Ei	c							
Damage Propagation Energy, Ep	h							
Maximum Energy Absorption, Em	m							
Total Energy Absorption (loss), Et	a							
Volumetric damage zone size (C-Scan)	r							
Nonvisible damage area	k							

Number positive attributes							
Number negative attributes							
Number equivalent measures							
Number knowledge gaps							

Note: This can serve as a baseline for evaluating one's concept against only impact resistance criteria. In a real design problem the critical few QM's identified here would be incorporated with those of the other design considerations.

APPENDIX F
TQD IMPACT TESTING

Impact testing customers' wants and quality metrics are given here along with the critical few impact testing metrics. A Pugh Concept Selection spreadsheet for impact testing shows a variety of test methods evaluated against a standard instrumented drop weight impact test method.

Table F.1 Mission Statement, Customer List and CW's

Mission Statement: Develop improved impact test and evaluation strategy and methods which allow designers to predict impact performance in real structures.

Top Customer Wants		**Rate of Importance**
1	Simple and predictive tests (design allowable prediction)	5
2	Understand, predict, control damage development process	5
3	Understand, predict, control Microcracking	5
4	Understand, predict, control Delaminations	5
5	Correlation of damage to residual strength	4
6	Low cost testing	4
7	Low cost/reliable damage detection and assessment	4
8	Reliability of damage assessment	4
9	Ease of Damage Assessment	3
10	Easy Test Data Acquistion and Reduction	3

Top Customers		**Rate of Importance**
CCM Consortium members-Industry and Government		5
Material suppliers		5
Fabricators of composite components		5
ASTM		5
CCM Staff and Faculty		4
Lab technicians-materials testers		4
CCM Students		3
End-User(OEM)	Aerospace design engineers	3
	Defense industry design engineers	3
	Automotive Industry	3

Rate of Importance

5- Very High
4-High
3-Average
2-Low
1-Very low

Table F.2 House of Quality for Evaluating and Correlating the CW's with QM's

Mission Statement: Develop improved impact test and evaluation strategy and methods which allow designers to predict impact performance in real structures.

CUSTOMER WANTS

Low cost/reliable
Understand, predict, co
Understand, predict, control M
Low cost testing
Correlation of damage to residual strength
Understand, predict, control damage developme
Simple and predictive tests (design allowable predictio

	Simpl	Unde	Corre	Low c	Unde	Unde	Low c	TOTALS
Rate of Importance	5	5	4	4	5	5	4	
Current Performance	2	3	3	1	2	2	3	
Top Competitors								
Instrumented Drop weight	4	4	3	3	3	3	3	
Customized instrumented impact	3	4	3	2	3	3	2	
Compression after impact	2	2	1	2	1	2	3	
Izod test	1	1	1	4	1	1	1	
Charpy	1	1	1	4	1	1	1	
Pendulum instrumented impact	3	4	3	3	3	4	4	
Test design in building-block approa	2	4	4	1	3	4	4	
Planned Performance	5	5	4	4	4	4	4	
Ratio of Improvement	2.5	1.7	1.3	4.0	2.0	2.0	1.3	
Leverage (1=low, 1.5=high)	1.5	1.5	1.4	1.3	1.5	1.5	1.2	10
Absolute Weight	18.8	12.5	7.5	20.8	15.0	15.0	6.4	96
Demand Weight	19.5	13.0	7.8	21.7	15.6	15.6	6.7	100

Table F.3 Impact Testing Criteria and House of Quality Correlations

Impact Testing Metrics

QUALITY METRICS	Simpl	Under	Correl	Low d	Under	Under	Low d	Points	%
Testing									
Time to prepare test specimens	++	++	++	++	++	++	++	900	5.5
ASTM standardization	++	++	++	++	++	++	++	900	5.5
# of industries using test procedure	++	++	++	++	++	++	++	900	5.5
statistical error (Coeff. of std. dev.)	++	++	++	++	++	++	++	900	5.5
# of test specimens required	++	++	++	++	++	++	++	900	5.5
Frequency of unique apparatus used	++	++	++	++	++	++	+	873	5.3
Dimensional constraints of test app	+	++	++	++	++	++	+	795	4.8
Time to prepare test apparatus	++	+	+	++	+	+	++	692	4.2
# of companies using test procedure	+	++	+	+	++	++	=	651	3.9
Time to acquire test data	++	+	+	=	++	++	+	617	3.7
Training costs for technicians	++	++	++		+	+	+	553	3.4
Energy range	++	+	+	+	+	+		545	3.3
Velocity range	++	+	+	+	+	+		545	3.3
Time to prepare test strategy	++	+	+	++	=		+	524	3.2
Reliability of test results	=	++	++	=	++	++	=	517	3.1
# of researchers using test procedur	=	++	++	=	++	++	=	517	3.1
Number of test specimens required	++			++	=	=	++	462	2.8
Cost of test specimens	++			++	=	=	+	436	2.6
# of citations in the literature	++			++			++	431	2.6
# of tests required	++			++			++	431	2.6
Cost of test apparatus and ancillary	+			++			+	326	2.0
Mass range of crosshead	+	=		=	+	+		289	1.8
Time to reduce test data	++	=	=		=	=	+	261	1.6
Supportability of test apparatus	=			++			+	248	1.5
NDE									
Cost associated with failure to ider	++	++	+	+	+	+	++	657	4.0
Reliability of NDE data	++	++	+	+	+	+	++	657	4.0
Training costs for inspectors/opera	+	++	=	++	=	=	++	509	3.1
Inspection costs	=	=	=	++	+	+	++	452	2.7
Cost of sensors	+	=	=	++	=	=	++	405	2.5
Time to identify critical damage	++			+			++	344	2.1
Frequency of inspections	=	=		++			++	288	1.7
cost of NDE equipment	=	+		+			++	253	1.5
Support costs for NDE equipment	=			+			+	161	1.0

Table F.4 Evaluation of Impact Testing Criteria with Pugh Concept Selection Process

Mission Statement: Develop improved impact test and evaluation strategy and methods to predict impact performance in real structures.

	Concept Descriptions
Benchmark	Inst. Drop weight-Dynatup M-8200 w/730-I Data Acq./conv. test strategy
1	Customized instrumented impact test apparatus and conv. test strategy
2	Compression after impact testing (Boeing 7260)
3	Izod testing (ASTM D-256)
4	Charpy testing (ASTM D-256)
5	Pendulum instrumented impact
6	Test design in building-block approach
7	Inst. Drop weight-Dynatup M-8250 w/830-I Data Acq. and conv. test strategy
8	Inst. Drop weight-Dynatup M-8200 w/730-I Data Acq. and exp. design strategy
9	Inst. Drop weight-Dynatup M-8250 w/830-I Data Acq. and exp. design strategy

		Concepts										
Quality Metrics		1	2	3	4	5	6	7	8	9	10	11
Frequency of unique apparatus used	h	-	-	S	S	-	-	S	S	S		
Number of test specimens required	m	-	-	-	-	-	-	S	+	+		
Training costs for technicians	a	-	-	S	S	-	-	+	S	+		
Reliability of test results	r	S	-	-	-	S	S	S	S	S		
ASTM standardization	k	-	+	-	-	-	S	S	S	S		
# of industries using test procedures		?	+	?	?	?	+	-	?	-		
# of companies using test procedure	B	?	S	?	?	?	+	-	?	-		
# of researchers using test procedures	e	+	S	-	-	+	-	-	-	-		
# of citations in the literature	n	S	S	-	-	S	S	-	-	-		
Time to acquire test data	c	-	-	-	-	-	-	+	S	+		
Time to reduce test data	h	-	-	-	-	-	-	+	+	+		
statistical error (Coeff. of std. dev.) in test results	m	?	?	?	?	?	?	+	+	+		
# of test specimens required	a	-	-	-	-	-	-	S	+	+		
# of tests required	r	-	-	-	-	-	-	S	+	+		
Cost of test apparatus and ancillary equipment	k	-	S	+	+	-	-	-	S	-		
Mean time between failure of test apparatus		-	S	+	+	-	-	?	S	?		
Energy range	B	+	S	+	+	+	+	S	S	S		
Velocity range	e	+	S	S	S	+	+	S	S	S		
Dimensional constraints of test apparatus	n	+	S	-	-	+	+	S	S	S		
Mass range of crosshead	r	+	S	+	+	+	+	S	S	S		
Size of test specimens required	k	-	-	+	+	-	-	S	S	S		
Temperature condition range	m	S	S	S	S	S	S	+	S	+		
R.H. conditioning range	a	S	S	S	S	S	S	+	S	+		
Time to prepare test strategy	r	S	S	S	S	S	-	S	-	-		
Time to prepare test specimens	k	S	S	S	S	S	-	S	+	+		
Cost of test specimens	k	?	-	+	+	S	-	S	+	+		
Time to prepare test apparatus	k	?	-	+	+	-	-	S	S	S		

Number of metrics better than Benchmark	+	5	2	5	5	5	6	6	6	10		
Number of metrics worse than Benchmark	-	11	9	10	10	11	13	5	3	6		
Number of metrics the same as the Benchmark	S	6	13	7	7	6	5	13	14	8		
Number of knowledge gaps	?	3	1	3	3	3	1	1	2	1		

APPENDIX G
TEST MATRIX

The test matrix, Table G, shows the impact and static load tests which were performed to collect the raw data presented in Appendix H and analyzed in Chapters 4, 6, and 7. Additional static load-deflection tests of Aluminum plates were conducted on the apparatus described in Chapter 6 for the purpose of verifying the load-deflection models developed in Chapter 4.

TABLE G TEST MATRIX

Instrumented Impact Tests

Material System	Layup	Test Specimen Spt.	# of replicates @ 5 J	15 J	40 J	
AS4/35601-6	16 ply	w/reduction cyl. (5.08 cm dia.)	3	3	3	*Total Specimens*
		wo/reduction cyl. (6.35 cm dia.)	3	3	3	*18*
	32 ply	w/reduction cyl.	3	3	3	*Total Specimens*
		wo/reduction cyl.	3	3	3	*18*
	48 ply	w/reduction cyl.	3	3	3	*Total Specimens*
		wo/reduction cyl.	3	3	3	*18*
AS4/PEEK	16 ply	w/reduction cyl.	3	3	3	*Total Specimens*
		wo/reduction cyl.	3	3	3	*18*
	32 ply	w/reduction cyl.	3	3	3	*Total Specimens*
		wo/reduction cyl.	3	3	3	*18*
	48 ply	w/reduction cyl.	3	3	3	*Total Specimens*
		wo/reduction cyl.	3	3	3	*18*

Static Loading Tests

Material System	Layup	Test Specimen Spt.	# of replicates @ to 200 lbs.	
AS4/35601-6	16 ply	w/reduction cyl.	3	*Total Specimens*
		wo/reduction cyl.	3	*6*
AS4/PEEK	16 ply	w/reduction cyl.	3	*Total Specimens*
		wo/reduction cyl.	3	*6*

APPENDIX H

IMPACT TEST DATA

Instrumented impact test data is presented in Table H.1 for selected impact tests conducted at 5, and 15 Joules.for 16 and 32 ply AS4/3501-6 and AS4/PEEK (APC-2) specimens with and without reduction cylinder. Examples of specimen identification scheme:

1) **APC16P05J** = AS4/PEEK (**APC**-2) **16 P**ly [±45/0/90]2s, impacted at **5 J**oules (nominal) with reduction cylinder (annulus diameter-5.08 cm)

2) **AS432P15JN** = **AS4**/3501-6 **32 P**ly [±45/0/90]4s, impacted at **15 J**oules (nominal), (**N**) without reduction cylinder (annulus diameter-6.35 cm)

Data presented for damage area (cm^2) is calculated from grayscale enhanced C-scan images as described in Chapter 6. All other data is output from the GRC Model 730-I Data Acquistion System. A complete data set containing 48 ply coupons and 40 Joule tests is retained in an electronic Excel spreadsheet and digital image files on CCM ultrasonic C-scan enhanced image system.

Table H.1 Impact Test Results for Selected Tests

Specimen ID	Impact Velocity (m/sec)	Impact Energy (Joules)	Total Time (msec)	Total Energy absorbed (Joules)	Maximum Deflection (mm)	At Maximum Load: Time (msec)	At Maximum Load: Load (kn)	At Maximum Load: Energy (Joules)	At Maximum Load: Deflection (mm)	Dam. Area (cm2)	
APC16P05J	1.71	6.27	5.92	5.08	6.09	2.60	1.66	3.28	3.89	1.35	
APC16P05J	1.71	6.28	8.03	5.08	6.21	2.35	1.41	2.76	3.81	1.57	
APC16P05J	1.71	6.28	8.00	5.03	6.33	2.82	1.34	3.36	4.17	1.35	
APC16P05JN	1.72	5.33	6.92	5.23	7.43	3.55	1.32	3.62	5.31	1.44	
APC16P05JN	1.73	5.38	7.00	5.25	7.27	3.20	1.28	3.44	4.79	1.40	
APC16P05JN	1.72	5.37	6.60	5.26	6.85	3.35	1.32	3.80	4.89	1.45	
APC16P15J	2.99	16.09	10.85	13.35	19.93	1.40	1.66	3.69	4.01	4.88	Near penetration
APC16P15J	2.98	16.08	14.70	12.83	27.34	1.00	1.62	1.99	2.93	4.02	Near penetration
APC16P15J	2.98	16.07	16.05	12.84	29.63	1.30	1.66	3.00	3.76	4.33	Near penetration
APC16P15JN	2.98	16.05	10.42	13.63	19.33	1.13	1.54	2.41	3.27	4.28	Near penetration
APC16P15JN	2.99	16.09	10.52	13.48	19.48	1.13	1.60	2.55	3.27	4.29	Near penetration
APC16P15JN	2.98	16.08	12.50	12.97	23.56	1.47	1.63	3.63	4.23	4.28	Near penetration
APC32P05J	1.71	5.26	2.97	5.07	3.02	1.60	2.75	3.61	2.16	0.45	
APC32P05J	1.71	5.30	2.92	5.12	2.98	1.52	2.79	3.76	2.17	0.44	
APC32P05J	1.71	5.30	2.97	5.12	3.01	1.47	2.80	3.59	2.14	0.46	
APC32P05JN	1.71	5.25	3.05	5.06	3.08	1.20	2.45	2.77	1.82	0.25	
APC32P05JN	1.71	5.27	3.17	5.07	3.21	1.25	2.39	2.78	1.90	0.27	
APC32P05JN	1.71	5.26	3.28	5.08	3.32	1.35	2.31	2.90	2.04	0.29	
APC32P15J	2.99	16.10	3.30	14.93	5.94	1.07	5.15	6.73	2.93	10.32	
APC32P15J	2.99	16.12	3.40	14.97	6.10	1.20	4.28	7.60	3.23	9.97	
APC32P15J	2.99	16.11	3.37	14.98	6.06	1.27	4.23	8.05	3.39	11.49	
APC32P15JN	2.99	16.14	3.60	15.19	6.39	1.07	4.35	5.85	2.97	7.44	
APC32P15JN	2.99	16.16	3.77	15.08	6.73	1.62	3.93	9.60	4.19	6.28	
APC32P15JN	2.99	16.14	3.67	15.16	6.54	1.62	4.07	9.73	4.15	6.78	
AS416P05J	1.71	5.26	6.75	4.91	7.00	1.70	1.27	1.58	2.76	6.23	
AS416P05J	1.71	5.27	6.28	4.98	6.48	2.30	1.54	2.69	3.55	6.23	
AS416P05J	1.70	5.20	6.75	4.99	7.32	3.17	1.84	3.08	4.91	10.78	
AS416P05JN	1.72	5.32	6.50	5.14	6.67	2.38	1.42	2.59	3.70	4.53	
AS416P05JN	1.72	5.32	6.22	5.16	6.41	2.67	1.44	3.12	4.04	4.78	
AS416P05JN	1.71	5.30	6.63	5.06	6.81	2.52	1.41	2.89	3.85	4.87	
'AS416P15J	2.83	14.42	10.42	11.69	18.84	1.07	1.45	2.15	2.96	4.95	Near penetration
AS416P15J	2.98	16.03	15.18	13.06	27.56	0.95	1.59	2.00	2.77	4.95	Near penetration
AS416P15J	2.98	16.05	10.55	12.65	21.29	1.00	1.53	2.15	2.92	5.77	Near penetration
AS416P15JN	2.98	16.07	11.02	12.92	21.77	1.00	1.50	1.96	2.92	4.95	Near penetration
AS416P15JN	2.98	16.06	11.30	12.83	22.60	1.15	1.50	2.29	3.35	4.98	Near penetration
AS416P15JN	2.98	16.07	10.70	13.01	21.18	1.13	1.45	2.16	3.29	5.05	Near penetration
AS432P05J	1.70	5.21	3.90	4.91	3.90	0.66	2.09	1.19	1.06	8.30	
AS432P05J	1.70	5.21	3.97	4.87	3.99	0.77	2.34	1.51	1.26	8.30	
AS432P05J	1.66	4.96	3.72	4.62	3.87	0.82	2.42	1.61	1.28	8.41	
AS432P05JN	1.70	5.23	3.85	4.91	3.87	0.87	2.63	1.82	1.39	3.97	
AS432P05JN	1.71	5.25	3.88	4.95	3.90	0.90	2.32	1.82	1.43	3.95	
AS432P05JN	1.71	5.27	3.72	4.93	3.79	0.90	2.54	1.94	1.42	4.61	
AS432P15J	2.99	16.15	4.00	16.17	7.08	1.73	3.65	9.54	4.46	24.91	
AS432P15J	2.99	16.16	4.10	14.94	7.34	1.65	3.47	9.01	4.31	24.61	
AS432P15J	2.99	16.15	3.95	15.15	6.98	1.85	3.72	10.56	4.66	27.04	
AS432P15JN	2.99	16.12	4.13	15.17	7.30	1.73	3.48	9.16	4.49	21.00	
AS432P15JN	2.99	16.12	4.00	15.21	7.08	1.85	3.55	10.22	4.69	20.87	
AS432P15JN	2.99	16.08	4.05	15.13	7.18	1.80	3.54	9.75	4.62	23.85	